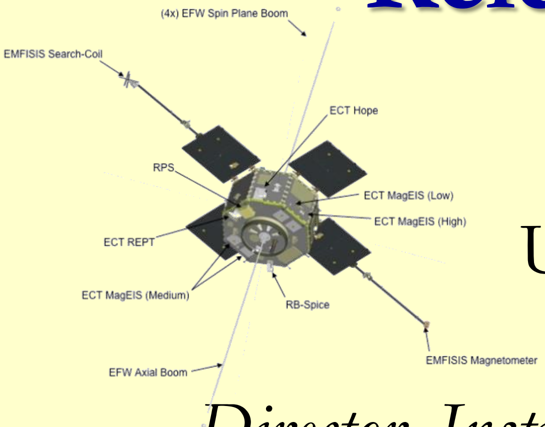
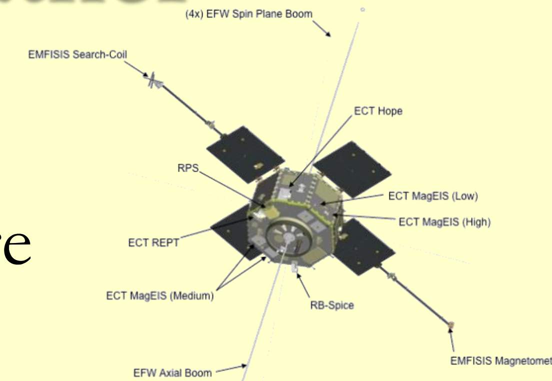
# The Van Allen Probes and New Results Relevant to Space Weather





## Harlan E. Spence

University of New Hampshire

*Professor of Physics and*

*Director, Institute for the Study of Earth, Oceans, and Space*


***11 April 2014***

***Space Weather Workshop***

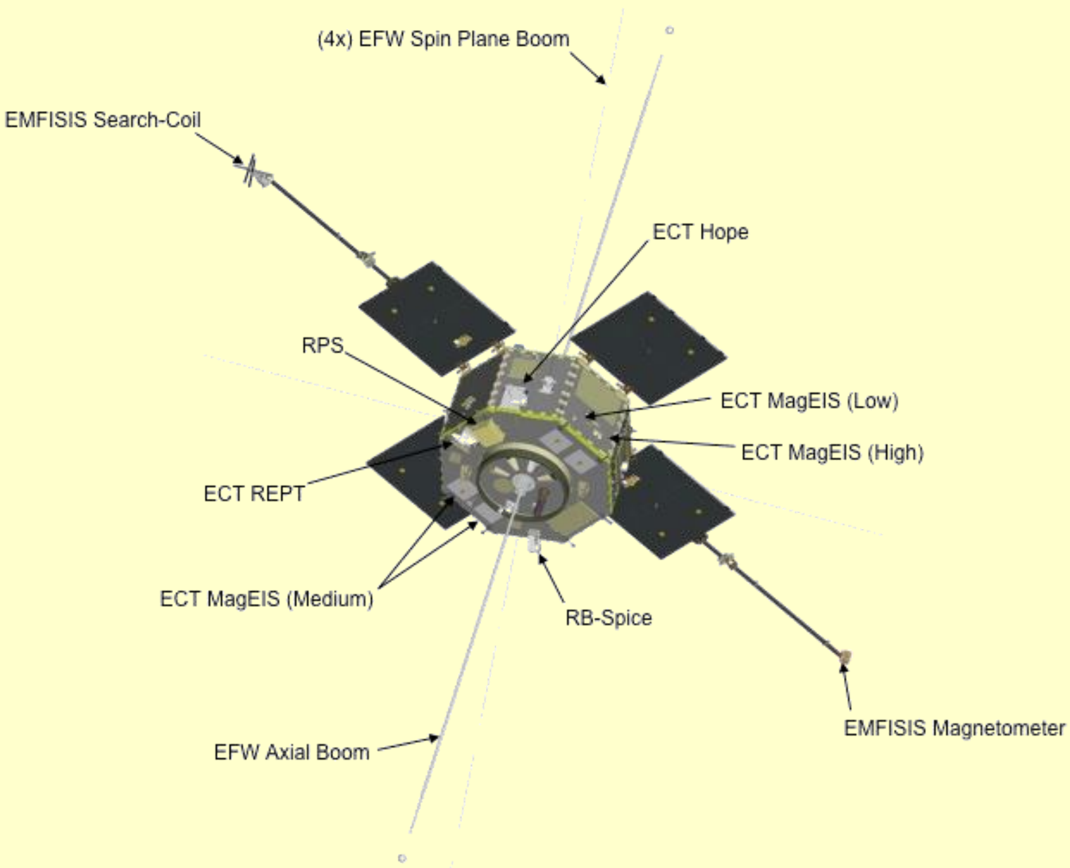

*Acknowledgements: Many thanks to the entire RBSP-ECT and and other Van Allen Probes Science Teams and especially Alex Boyd, Andy Gerrard, John Goldsten, Chia-Lin Huang, Lou Lanzerotti, Barry Mauk, Dick Maurer, Joe Mazur, and Larry Zanetti*


University of New Hampshire

Exploring the Extremes of Space Weather

Van Allen Probes

# Making Definitive Particle Measurements in Extremely Harsh Radiation Environments




**Particle Instruments**

- RBSP-ECT (PI, H. Spence)
  - HOPE (H. Funsten)
  - MagEIS (J. B. Blake)
  - REPT (D. N. Baker)
- RBSPICE (PI, L. Lanzerotti)
- RPS (PI, J. Mazur)
- ERM (PI, J. Goldsten)

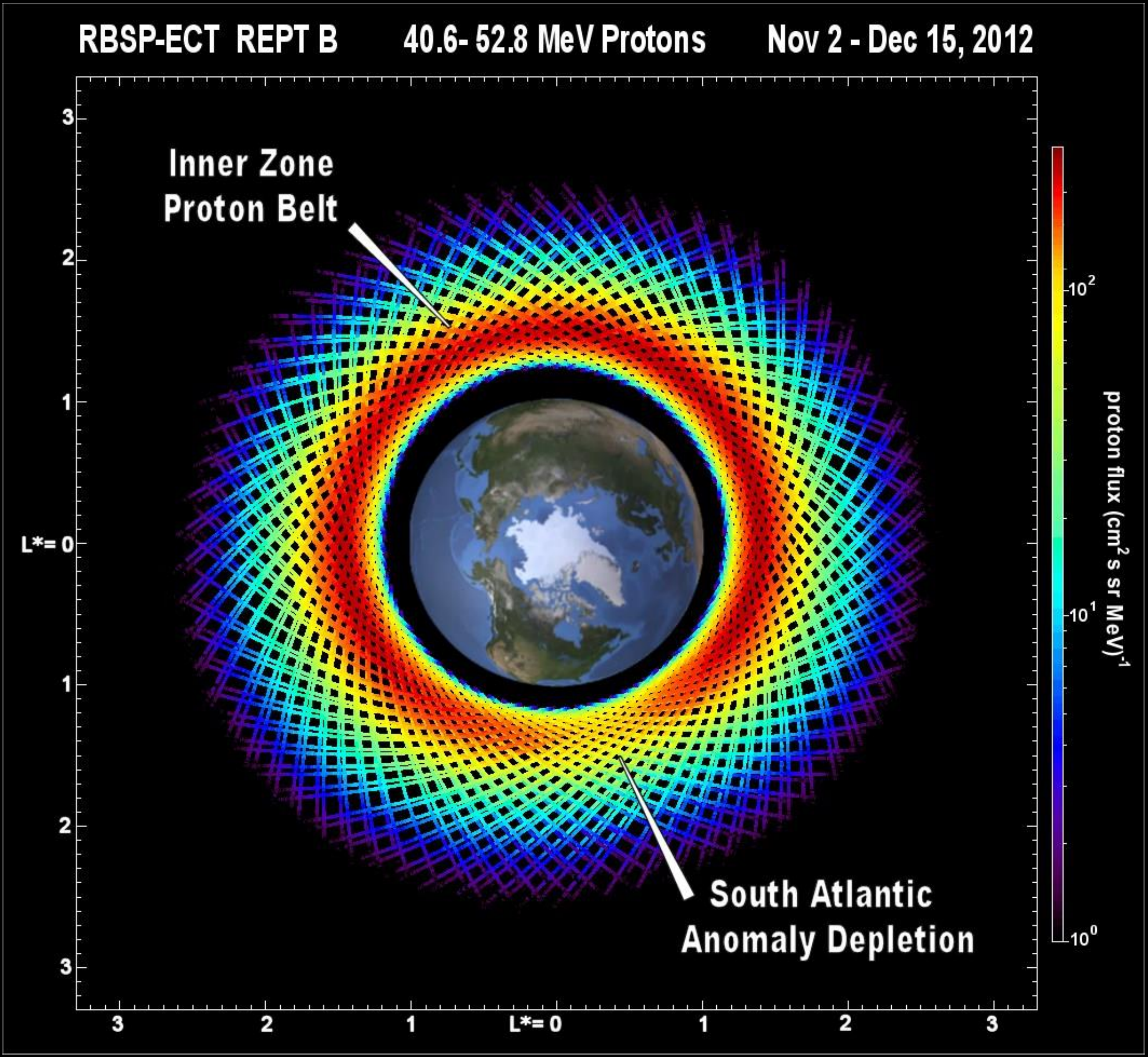
**Spaceweather Effects**

- Deep dielectric charging
- Surface charging
- SEU/SEE
- Dose and Dose Rate

**Underlying Physical Phenomena**

- Outer zone dynamics
- Inner zone dynamics
- Ring current dynamics

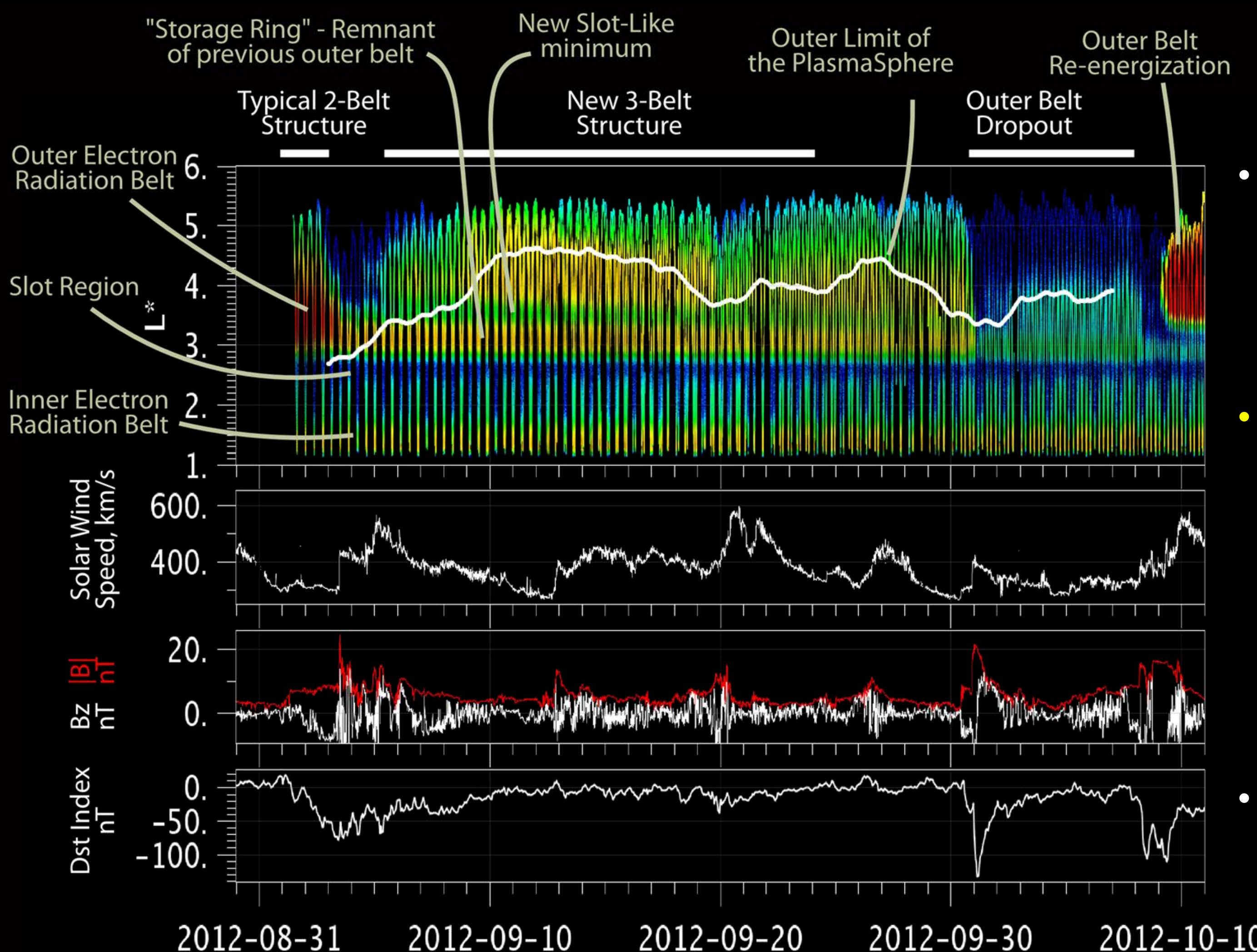
# REPT "images" of inner belt protons




- ~20 to 60 MeV proton data from REPT-A and –B reveal structure of inner belt
- Subsequent inbound passes of both spacecraft where proton intensity is used to color the spacecraft trajectory (projected into the eq. plane)
- Inner belt revealed dramatically and graphically after only a relatively short time during commissioning


Baker, D. N, V. Hoxie, A. Jaynes, A. Kale, S. G. Kanekal, X. Li, G. Reeves, and H. E. Spence,
James Van Allen and His Namesake NASA Mission, EOS, 2013.

# REPT "Storage Ring" discovery: a remarkable example of RB dynamics and structure

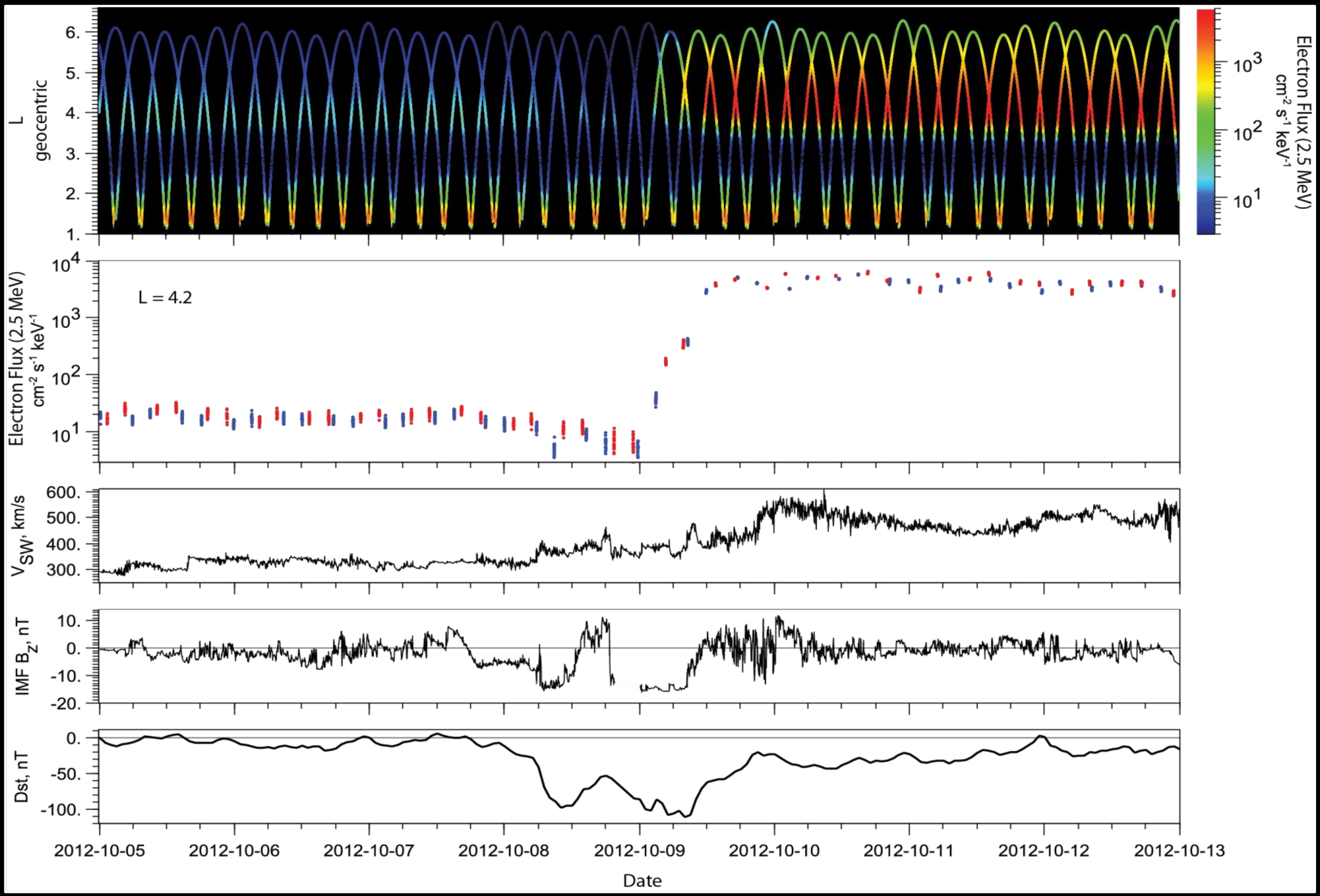



**REPT 4.5 MeV e- flux from both s/c plotted versus L and time**

- **Powerful processes sculpted and shaped radiation belts after instrument turn-on and up to present**
- **Baker et al. (Science, 2013) and Li et al. (JGR 2013) detail discovery of "storage ring": remnant inner sliver of outer zone electrons left behind after a belt-emptying event**
- **Outer zone reforms creating long-lived, 3-ring belt structure with theoretically-described decay (*)**

(*) Thorne, R. M., et al., Evolution and slow decay of an unusual narrow ring of relativistic electrons near L~3.2 following the September 2012 magnetic storm, Geophys. Res. Lett., DOI: 10.1002/grl.50627, 2013

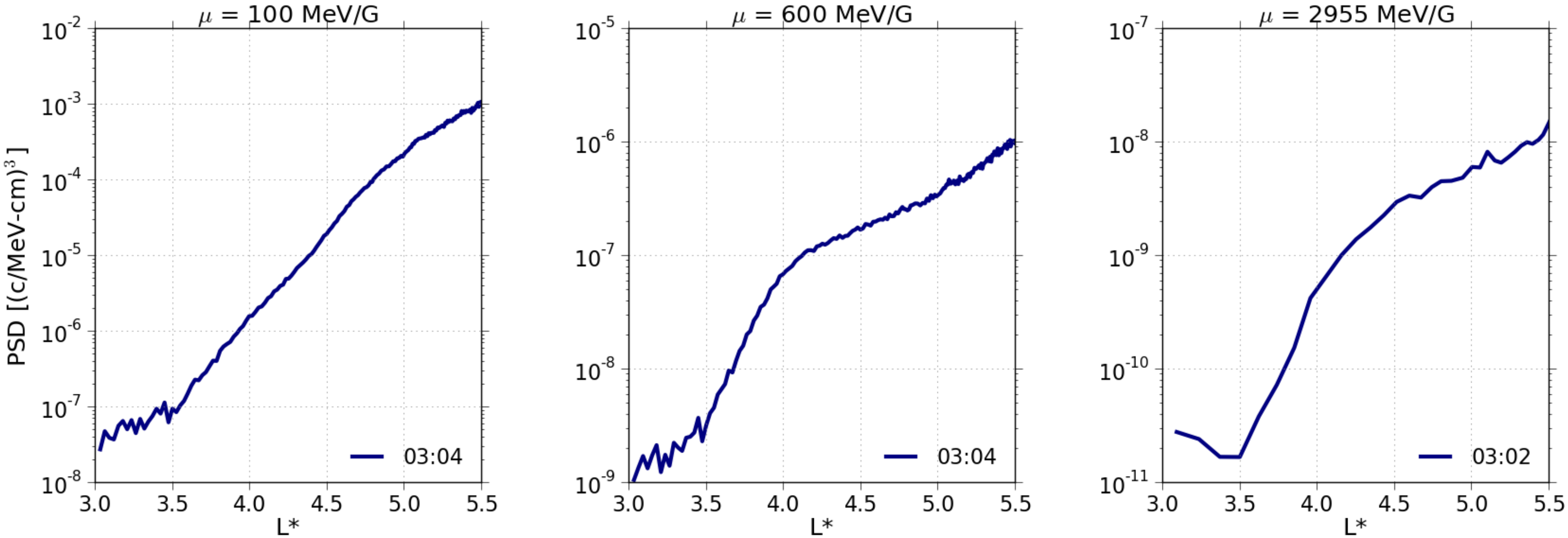
# Evolution of outer zone electrons during Oct 8-9 storm – Local acceleration in action



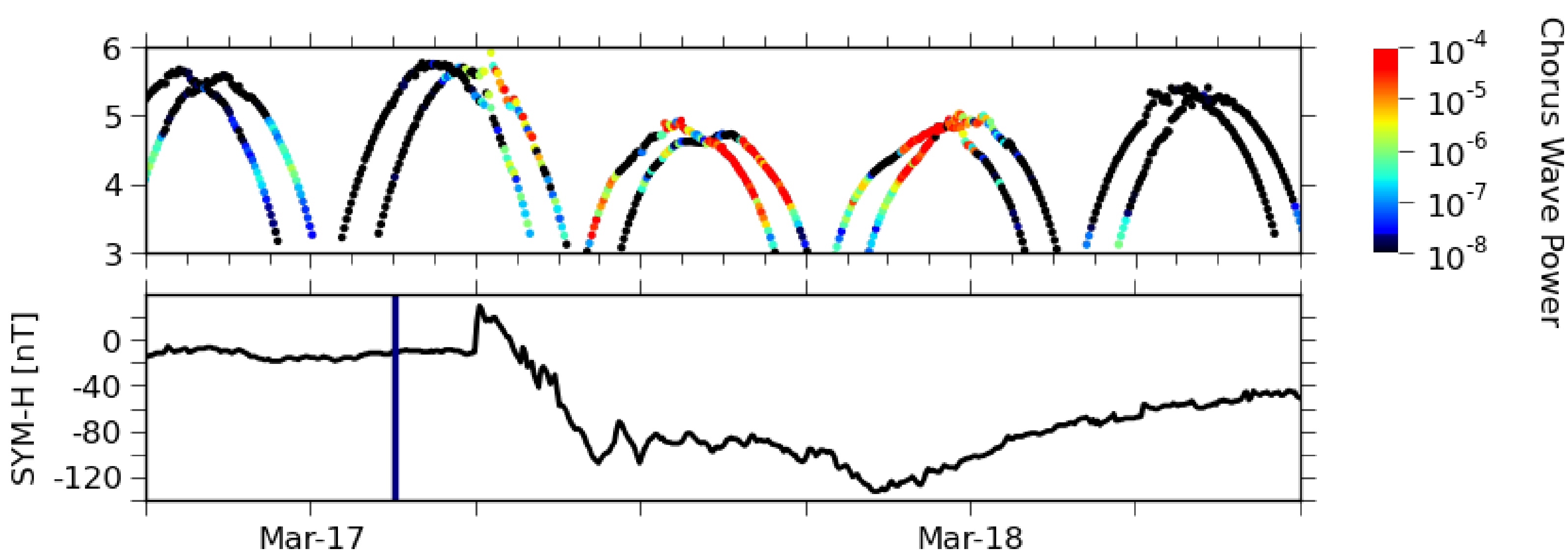

- **REPT ~2 MeV e- flux from both s/c plotted vs. L and time**
- **Moderate magnetic storm rapidly increases flux by many orders of magnitude**
- **Reeves et al. (Science, 2013) details confirmation that acceleration is local (WPI) not “radial” (first invariant)**

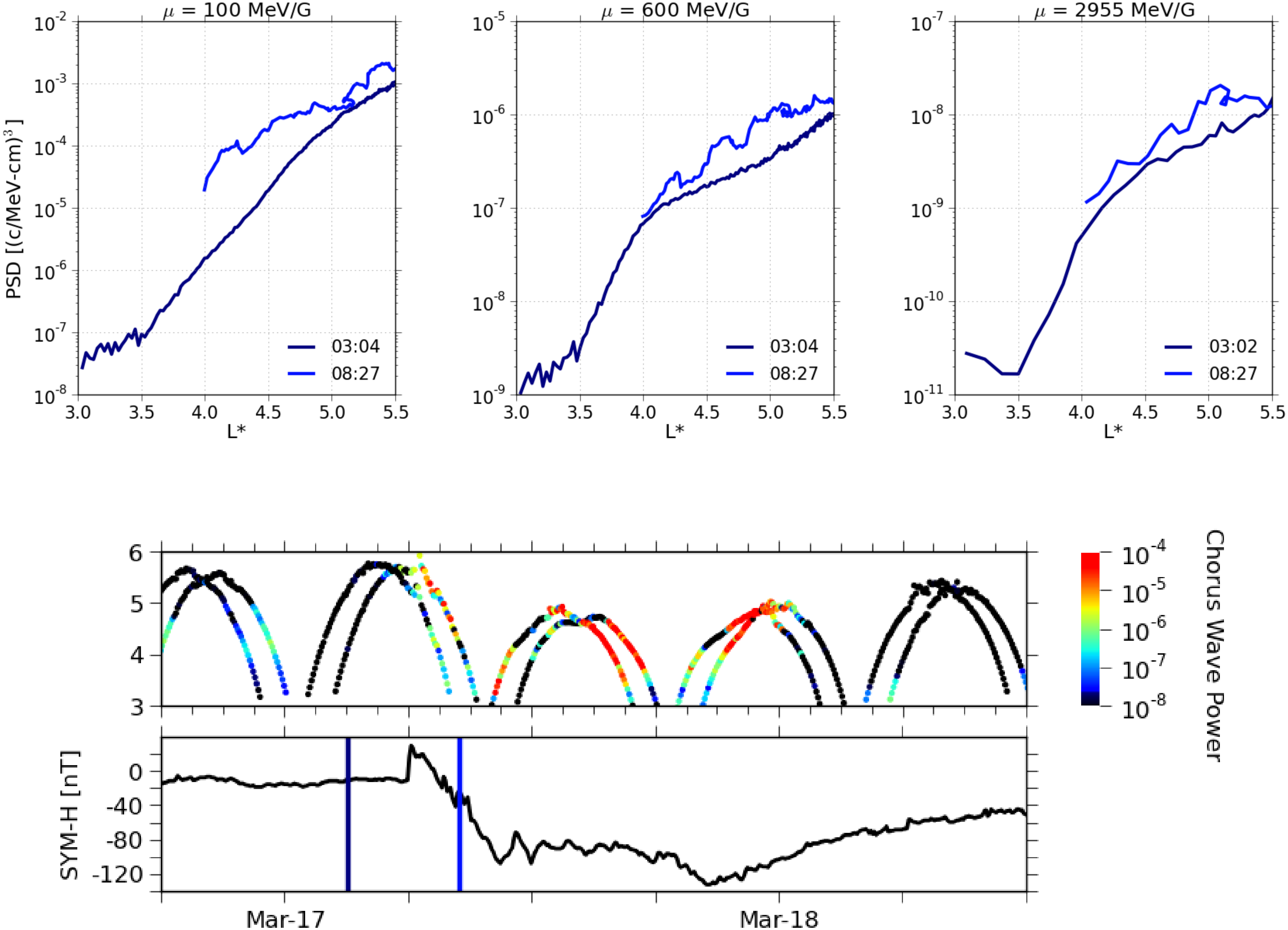
# The Role of the Seed Population and Chorus Waves in Radiation Belt Acceleration – Where do the Killer Electrons Come From?

Alexander Boyd et al.
(UNH Graduate Student)

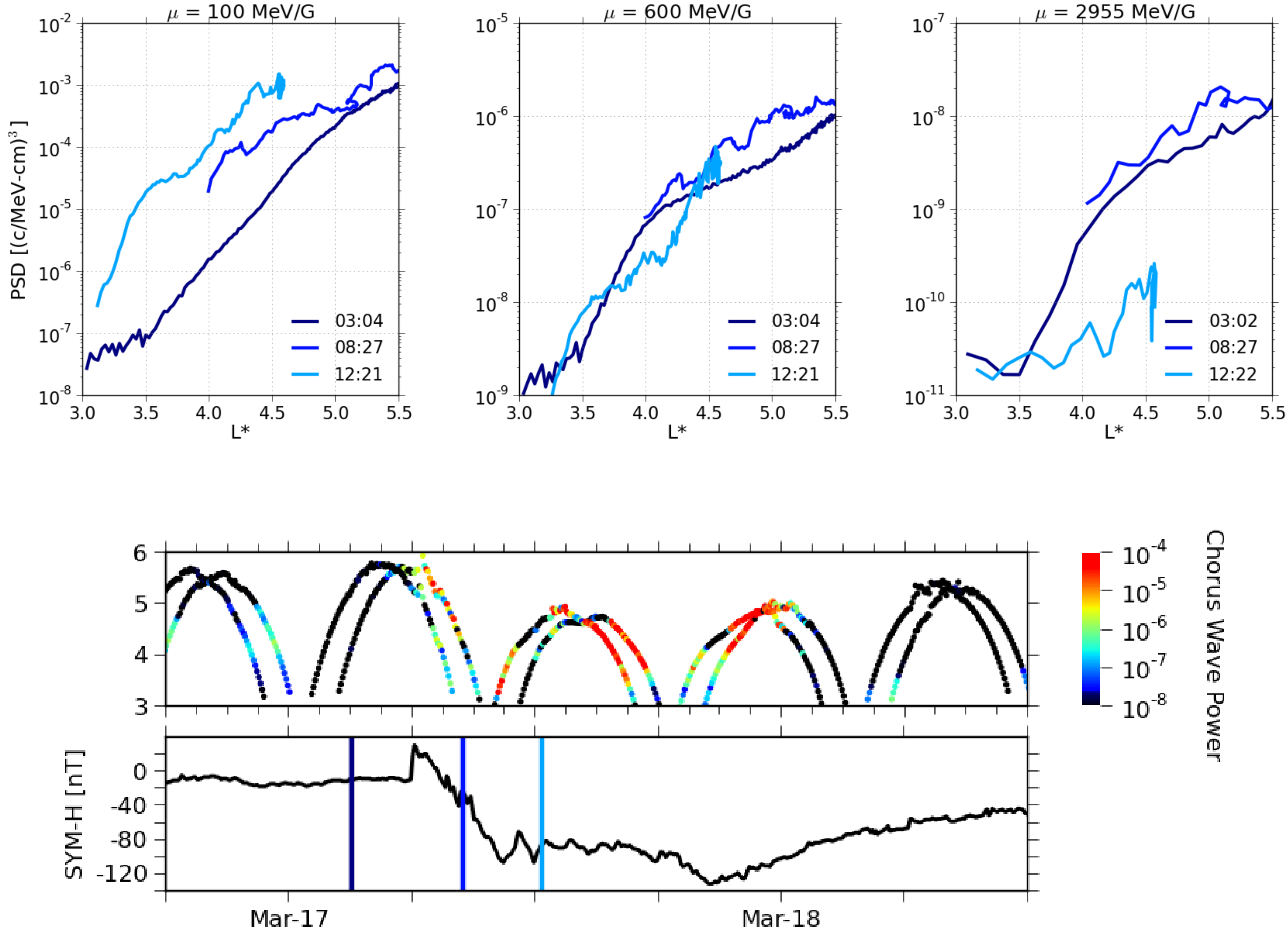



350 keV    1 MeV    3.5 MeV

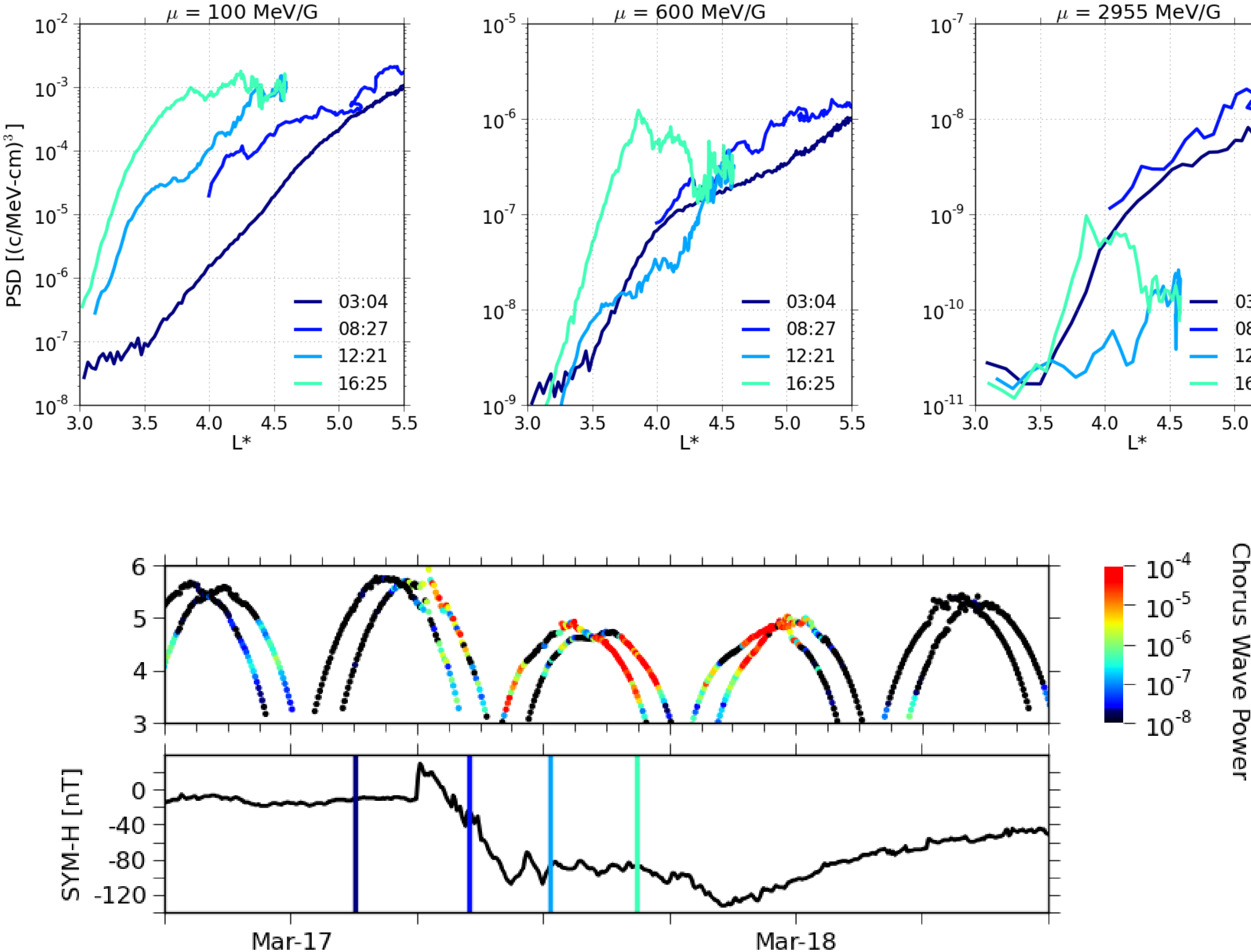




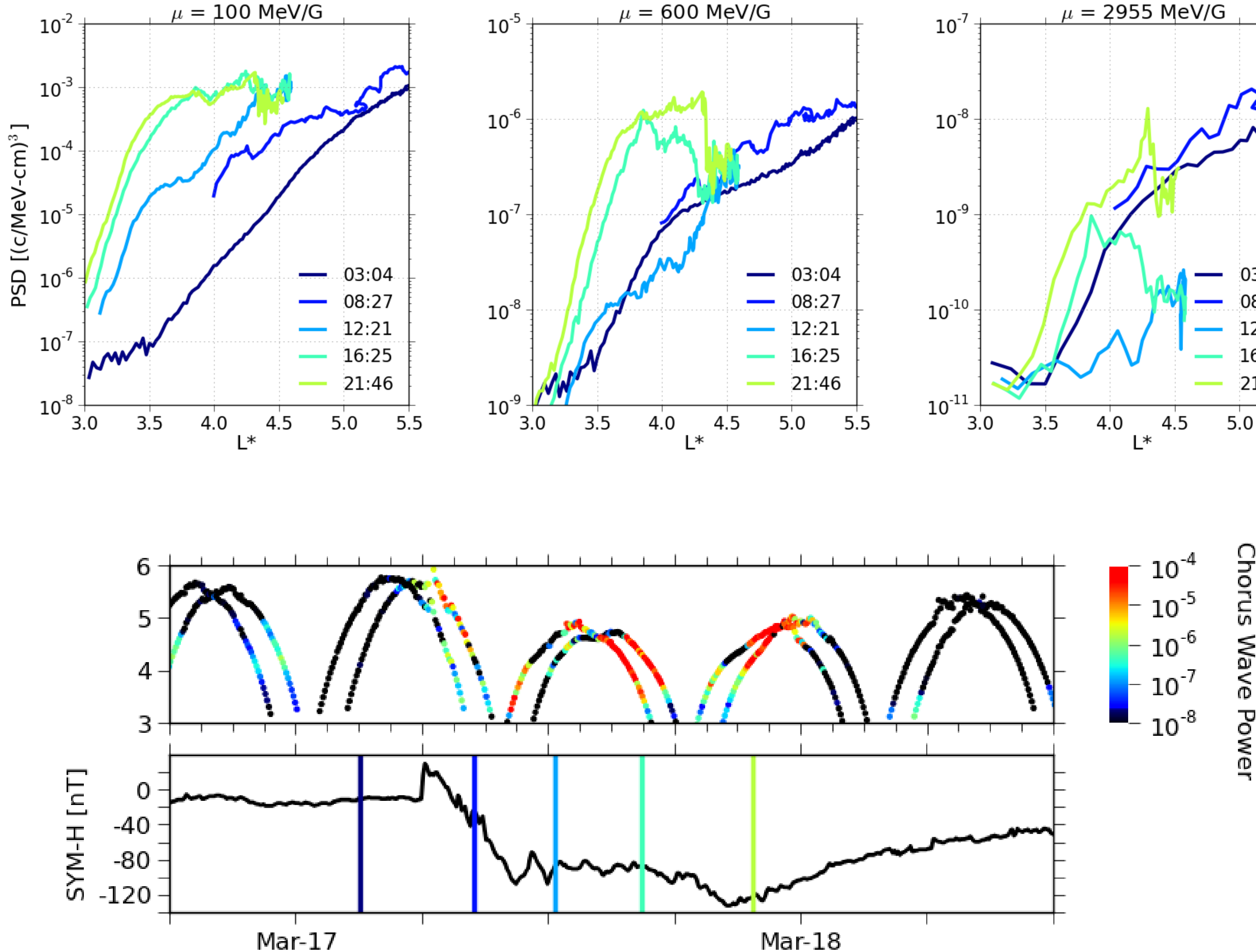
μ = 100 MeV/G
μ = 600 MeV/G
μ = 2955 MeV/G
PSD [(c/MeV-cm)^3]
L*
03:04
08:27
03:02
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18



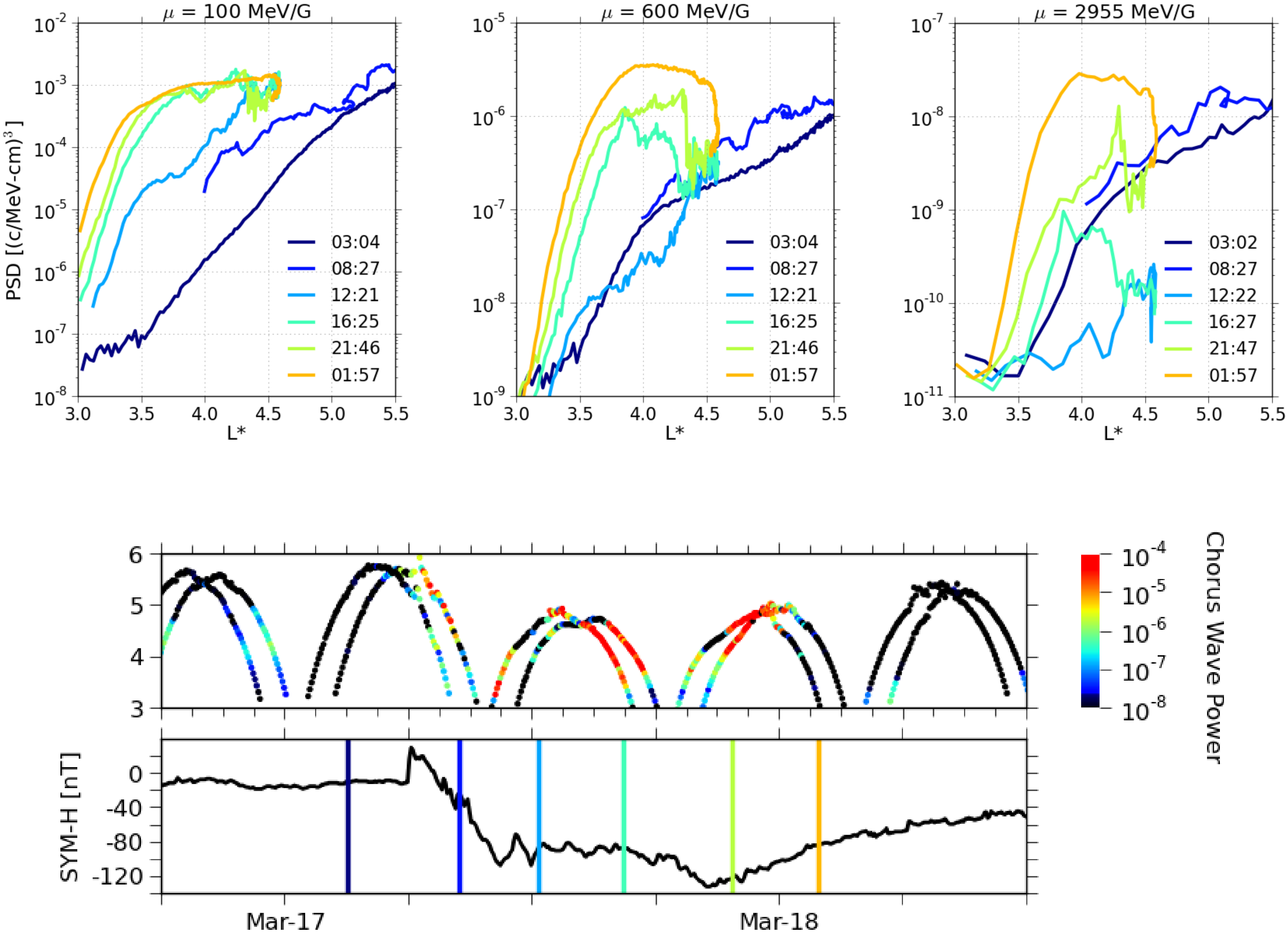
$\mu$ = 100 MeV/G
$\mu$ = 600 MeV/G
$\mu$ = 2955 MeV/G
PSD [(c/MeV-cm)$^3$]
L*
03:04
08:27
12:21
03:02
12:22
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18



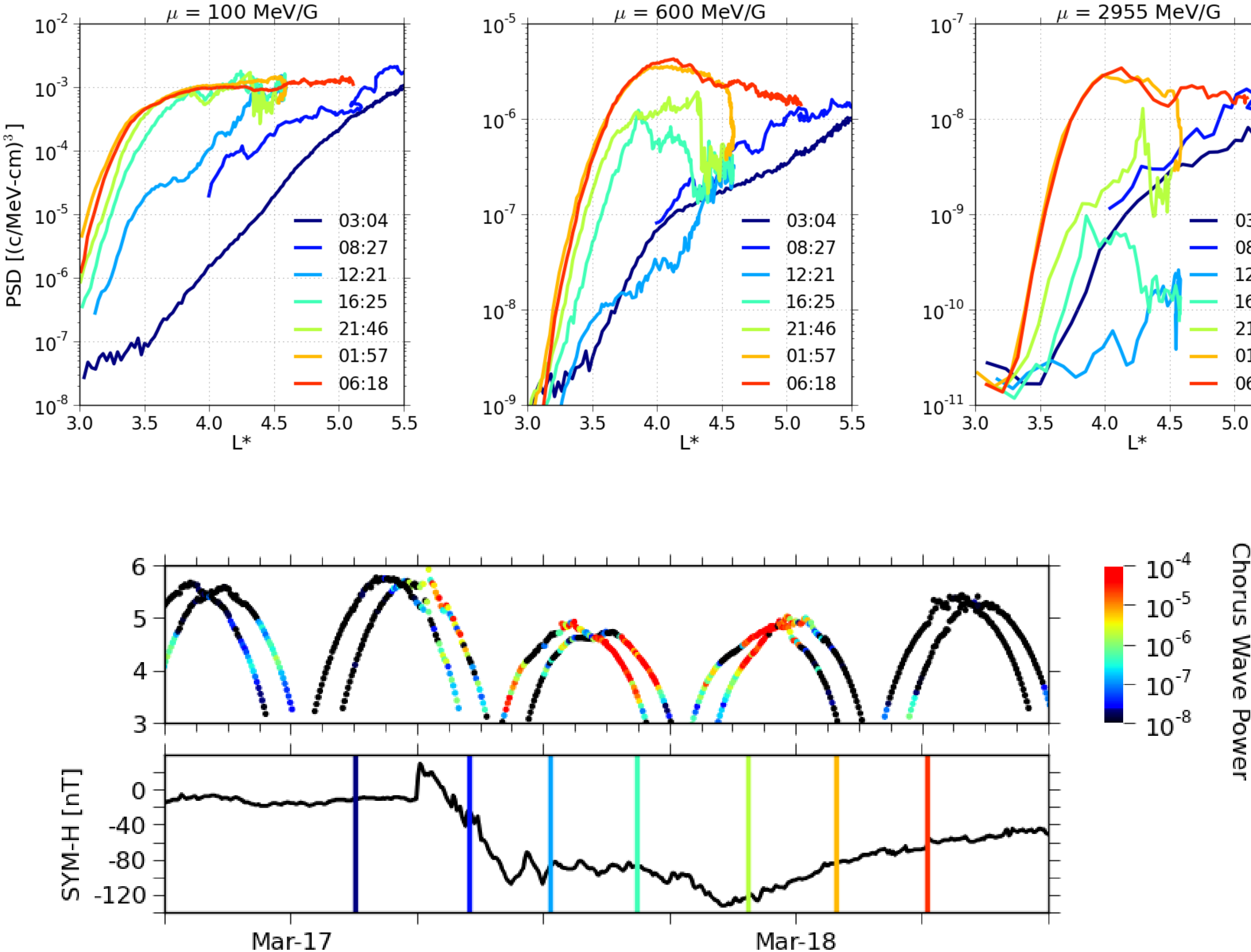
$\mu$ = 100 MeV/G
$\mu$ = 600 MeV/G
$\mu$ = 2955 MeV/G
PSD [(c/MeV-cm)$^3$]
L*
03:04
08:27
12:21
16:25
03:02
12:22
16:27
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18



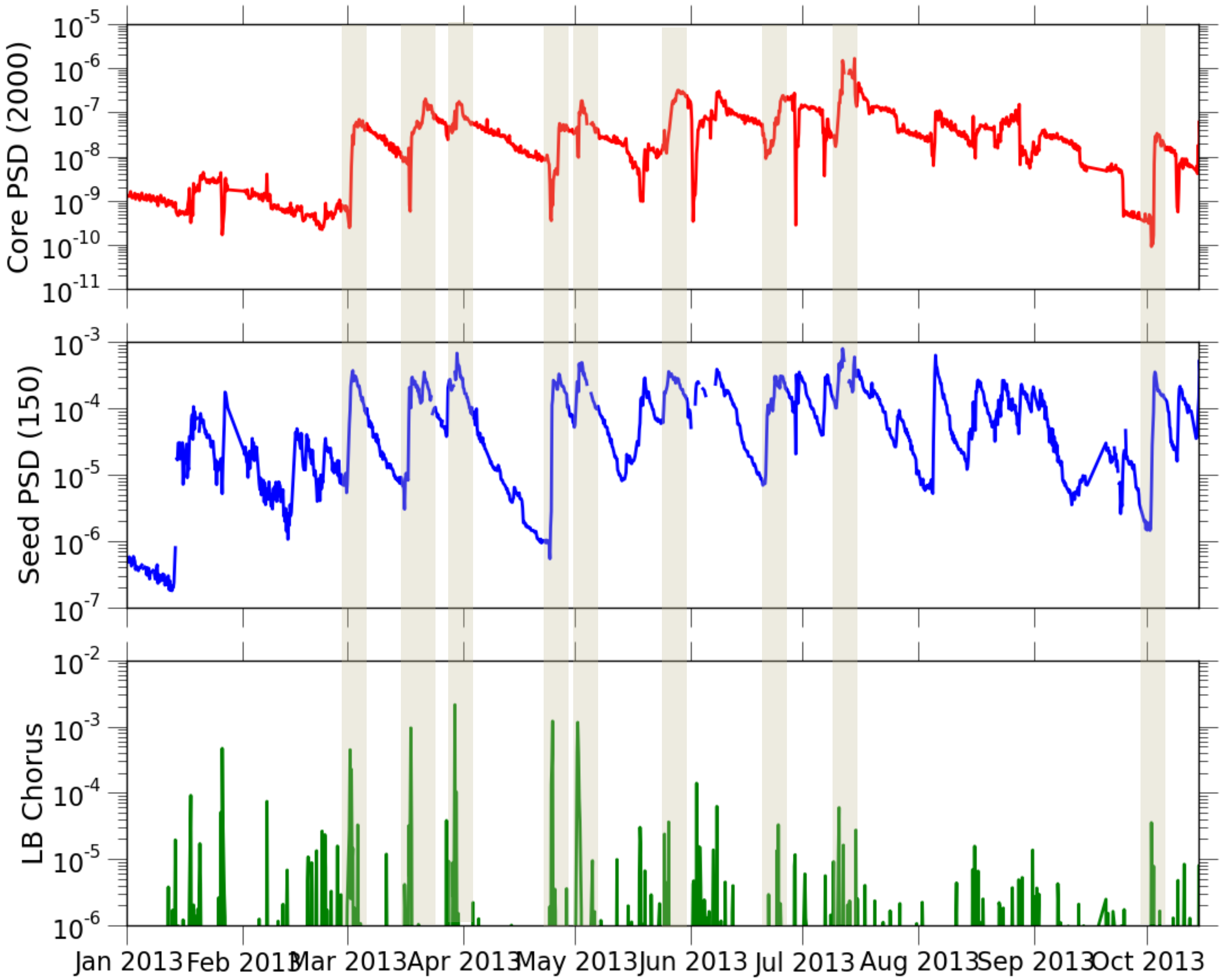
μ = 100 MeV/G
μ = 600 MeV/G
μ = 2955 MeV/G
PSD [(c/MeV-cm)^3]
L*
03:04
08:27
12:21
16:25
21:46
03:02
12:22
16:27
21:47
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18



μ = 100 MeV/G
μ = 600 MeV/G
μ = 2955 MeV/G
PSD [(c/MeV-cm)³]
L*
03:04
08:27
12:21
16:25
21:46
01:57
03:02
12:22
16:27
21:47
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18

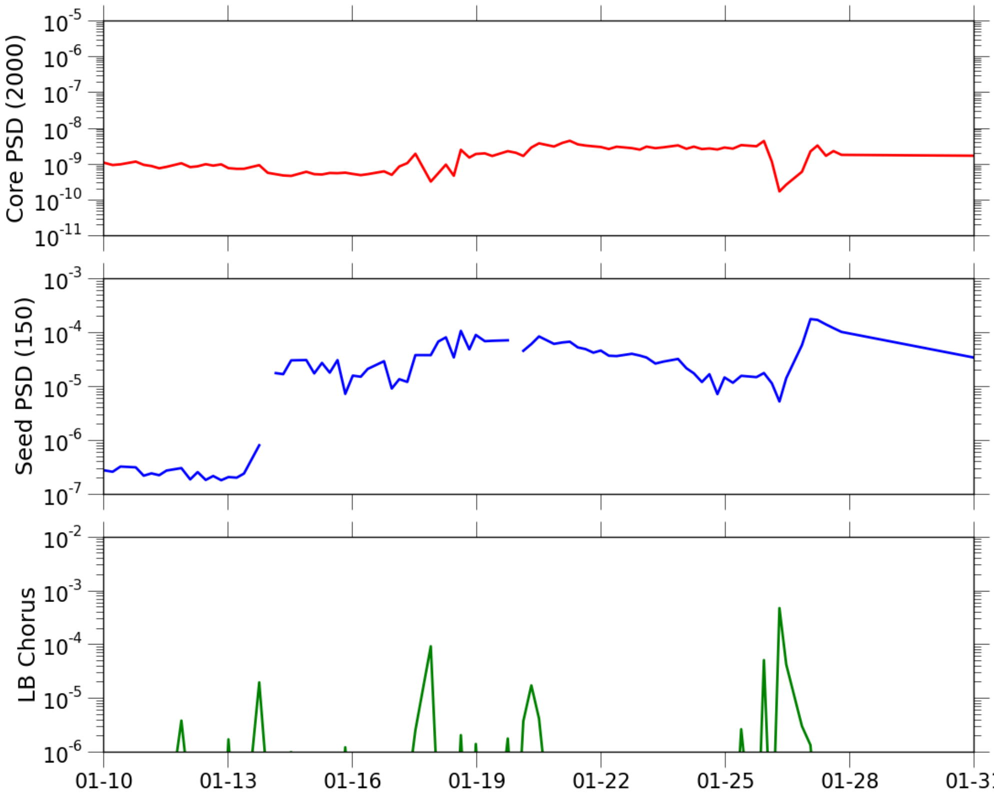


μ = 100 MeV/G
μ = 600 MeV/G
μ = 2955 MeV/G
PSD [(c/MeV-cm)^3]
L*
03:04
08:27
12:21
16:25
21:46
01:57
06:18
03:02
12:22
16:27
21:47
06:17
Chorus Wave Power
SYM-H [nT]
Mar-17
Mar-18

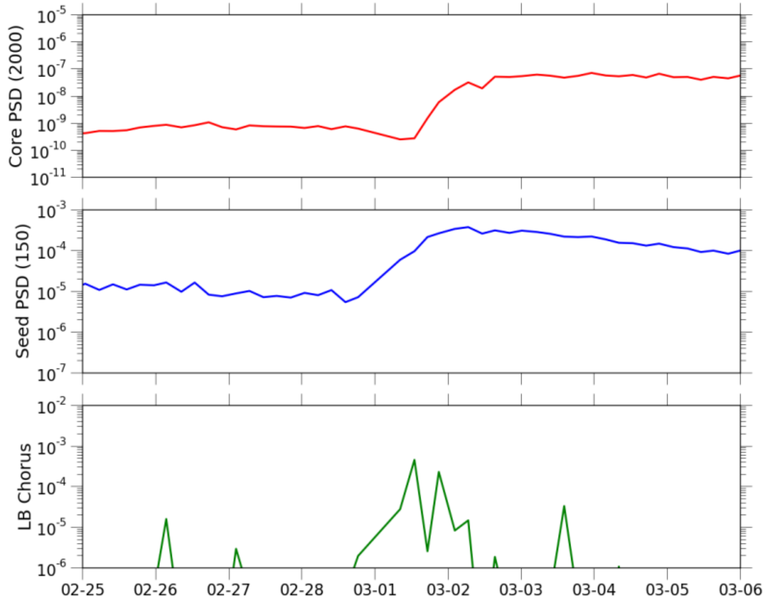


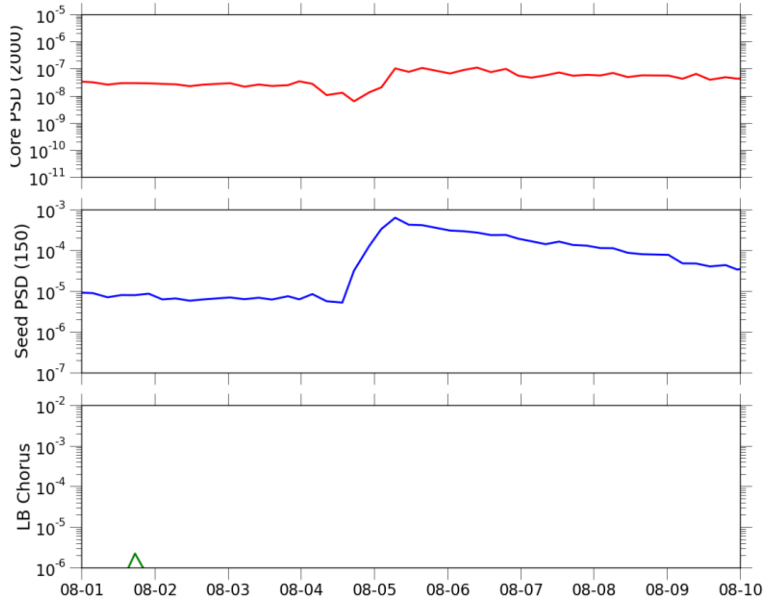
Core PSD (2000)
Seed PSD (150)
LB Chorus
Jan 2013
Feb 2013
Mar 2013
Apr 2013
May 2013
Jun 2013
Jul 2013
Aug 2013
Sep 2013
Oct 2013

# You need the seed population…



# …and you need the waves



# Quantifying Seed and Core Populations With The Total Radiation Belt Electron Content (TRBEC)

Chia-Lin Huang et al.

(UNH)

# Calculate TRBEC I

- Convert measured differential flux to phase space density in adiabatic invariant coordinates f(μ, K, L*) and calculate TRBEC from phase space density data by integrating through the three adiabatic invariants

- Phase space density is represented in canonical coordinates {***x***,***p***} and equivalently to {***J***, ***ϕ***}

$$Ne = \iint f(\vec{x},\vec{p})\,d\vec{x}\,d\vec{p} = \iint f(\vec{\phi},\vec{J})\,d\vec{\phi}\,d\vec{J} = (2\pi)^3 \int f(J_1,J_2,J_3)\,dJ_1 dJ_2 dJ_3$$

- J1, J2, J3 can be replaced with μ, K, L*

$$dN = (2\pi)^3 \bar{f}(\mu,K,L^*)\frac{\partial(J_1,J_2,J_3)}{\partial(\mu,K,L^*)}d\mu dK dL^*$$

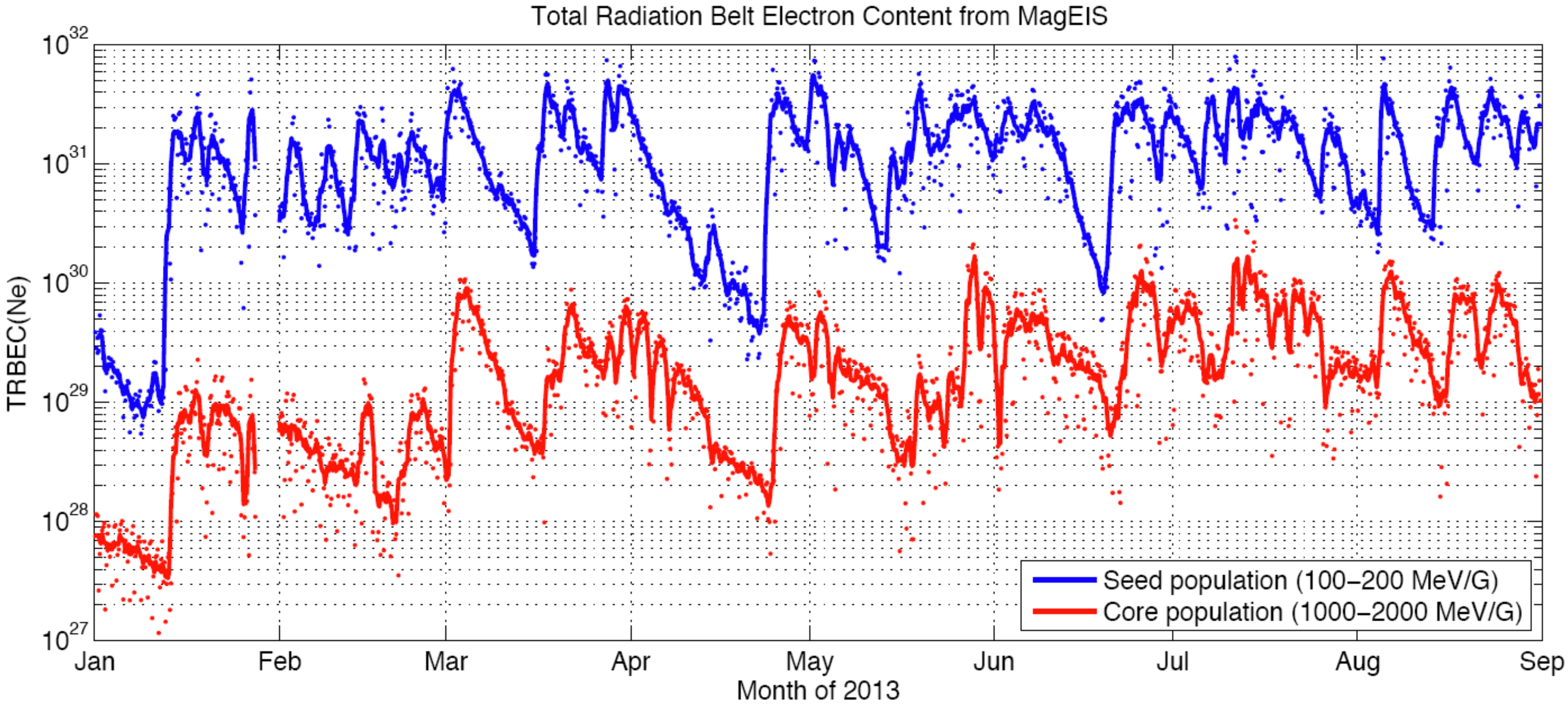
# Calculate TRBEC IV

- Number of electrons in an elemental phase space:

$$
\begin{aligned}
dN &= (2\pi)^3 \bar{f}(\mu, K, L^*) \frac{\partial(J_1, J_2, J_3)}{\partial(\mu, K, L^*)} d\mu dK dL^* \\
&= (2\pi)^3 \bar{f}(\mu, K, L^*) \frac{8\sqrt{2}\pi^2 m_0^{3/2} \mu_0}{R_E} \frac{\sqrt{\mu}}{L^{*2}} d\mu dK dL^* \\
&\approx 8.134 \times 10^{29}\, \bar{f}(\mu, K, L^*) \frac{\sqrt{\mu}}{L^{*2}} d\mu dK dL^*.
\end{aligned}
$$

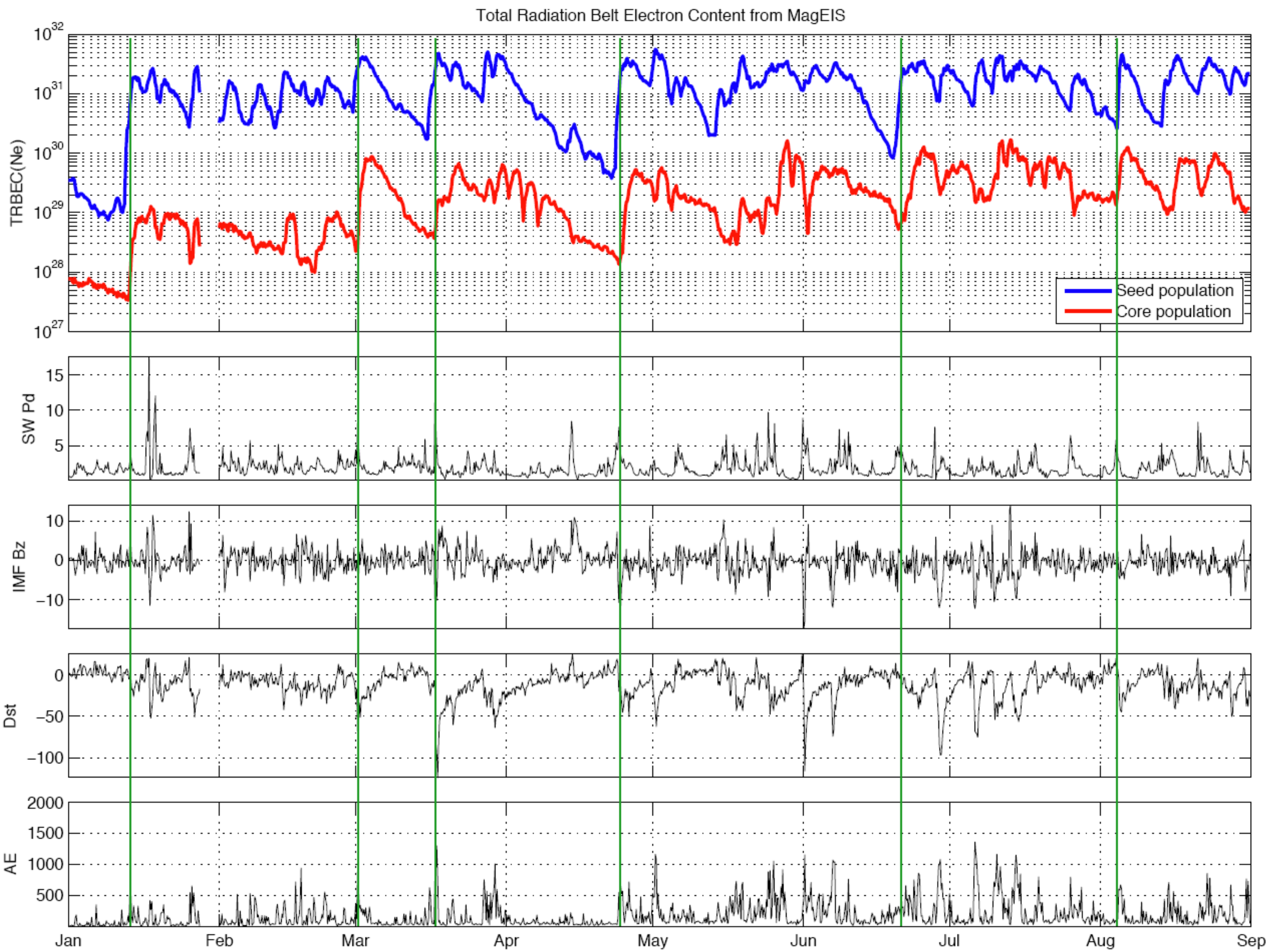
- Integrate μ with selected range for core and seed populations
- Integrate all K values
- Integrate half RBSP orbit to cover L* from 2.5 to ~6 (every 4.5 hours)

# MagEIS TRBEC




- TRBEC variability due to RBSP orbit on and off the magnetic equator, so we do a 5-point running average (~24 hour)
- Exclude very small TRBEC numbers (<10% of running averaged value) due to low K and L* coverage

# MagEIS TRBEC and SW Data



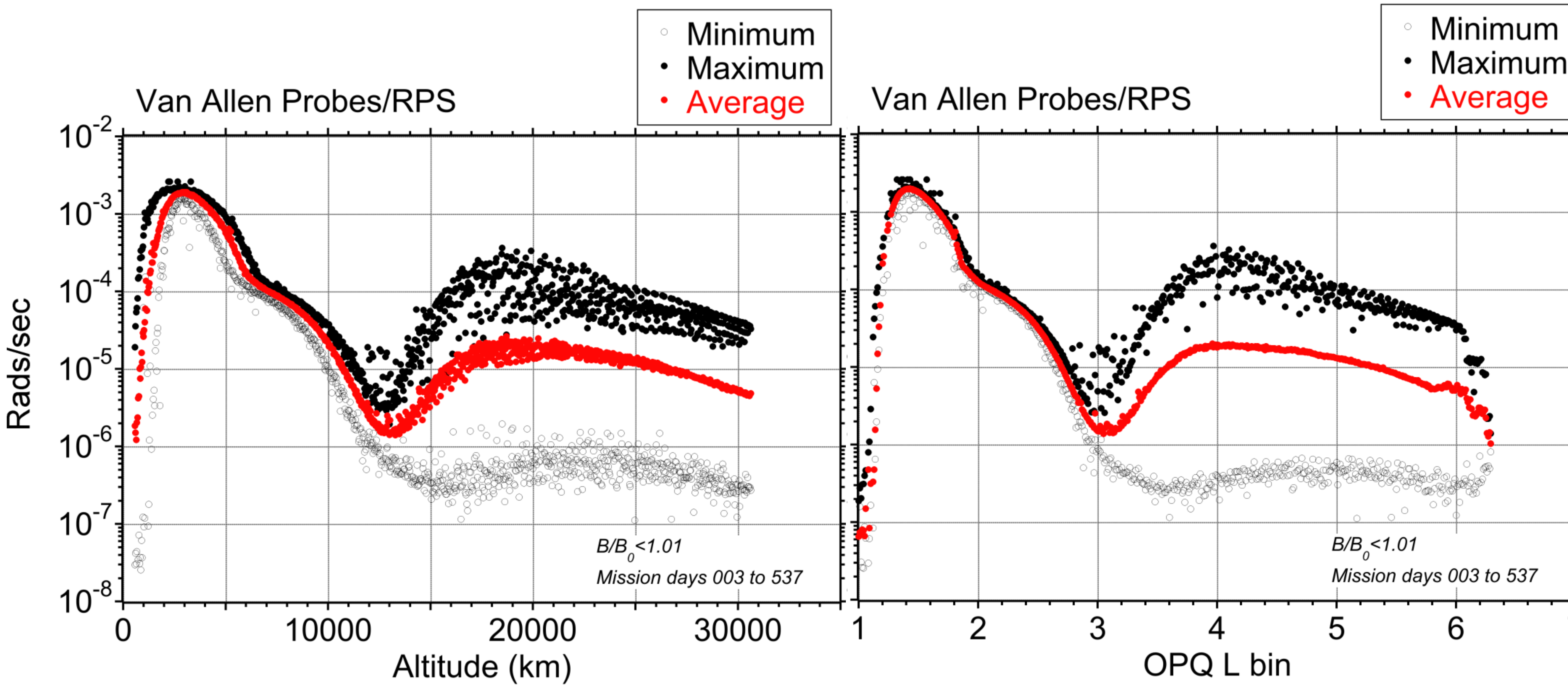
# TRBEC Applications

- Use single quantity to describe the whole electron belt and compare with model results
- Investigate the correlation and time difference between the seed and core populations
- Estimate the total electron loss due to magnetopause shadowing during storm main phases
- Calculate the electron acceleration time scale and loss time scale (lifetime)
- Correlate the solar wind condition and geomagnetic activity with TRBEC

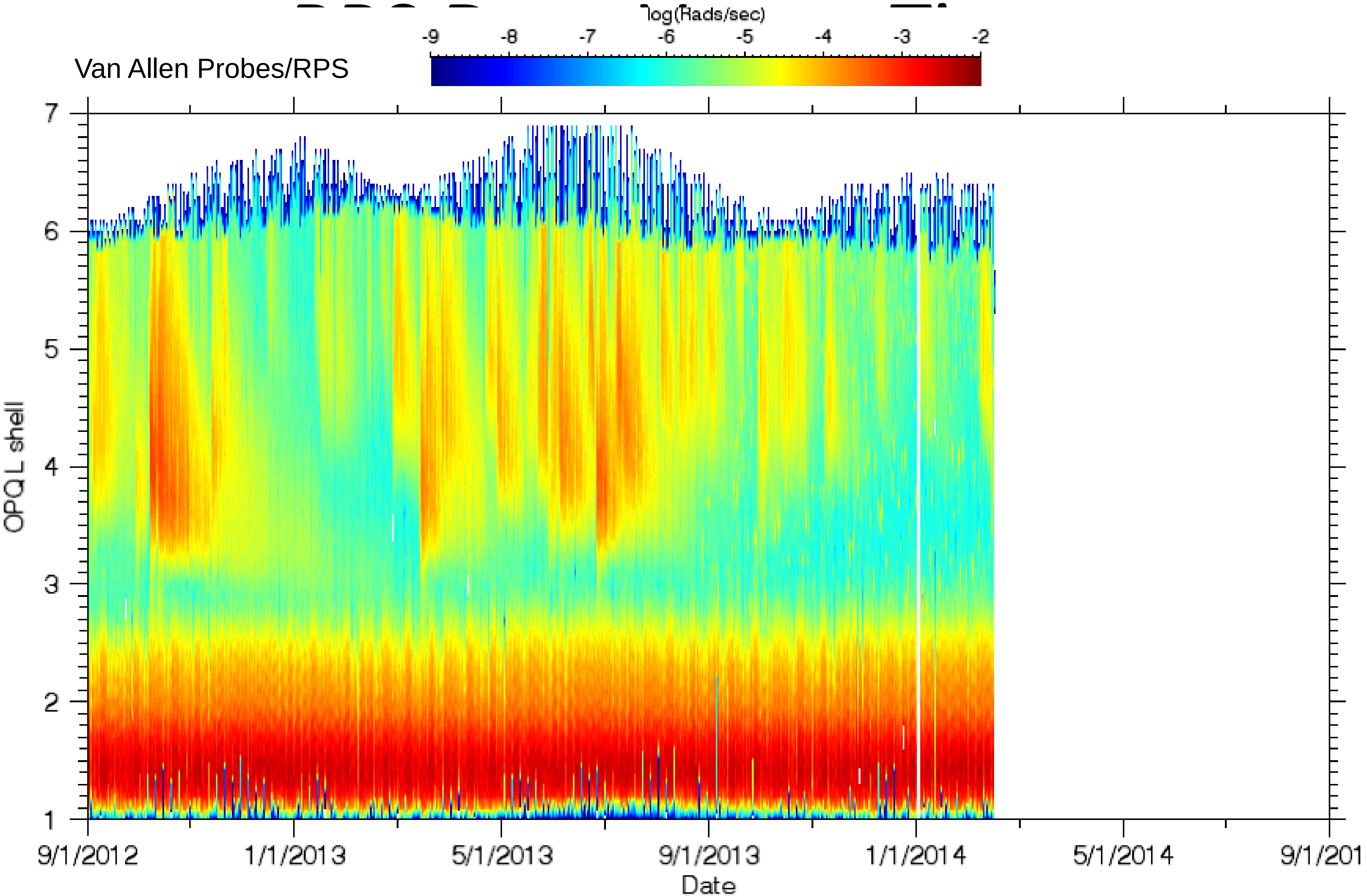
# Relativistic Proton Spectrometer (RPS) Dosimetry Results

Joe Mazur et al.
(The Aerospace Corporation)

# RPS Dosimetry: Total Dose Behind 540 mils




*Dose dominated by bremsstrahlung in outer belt and >50 MeV protons in the inner belt*

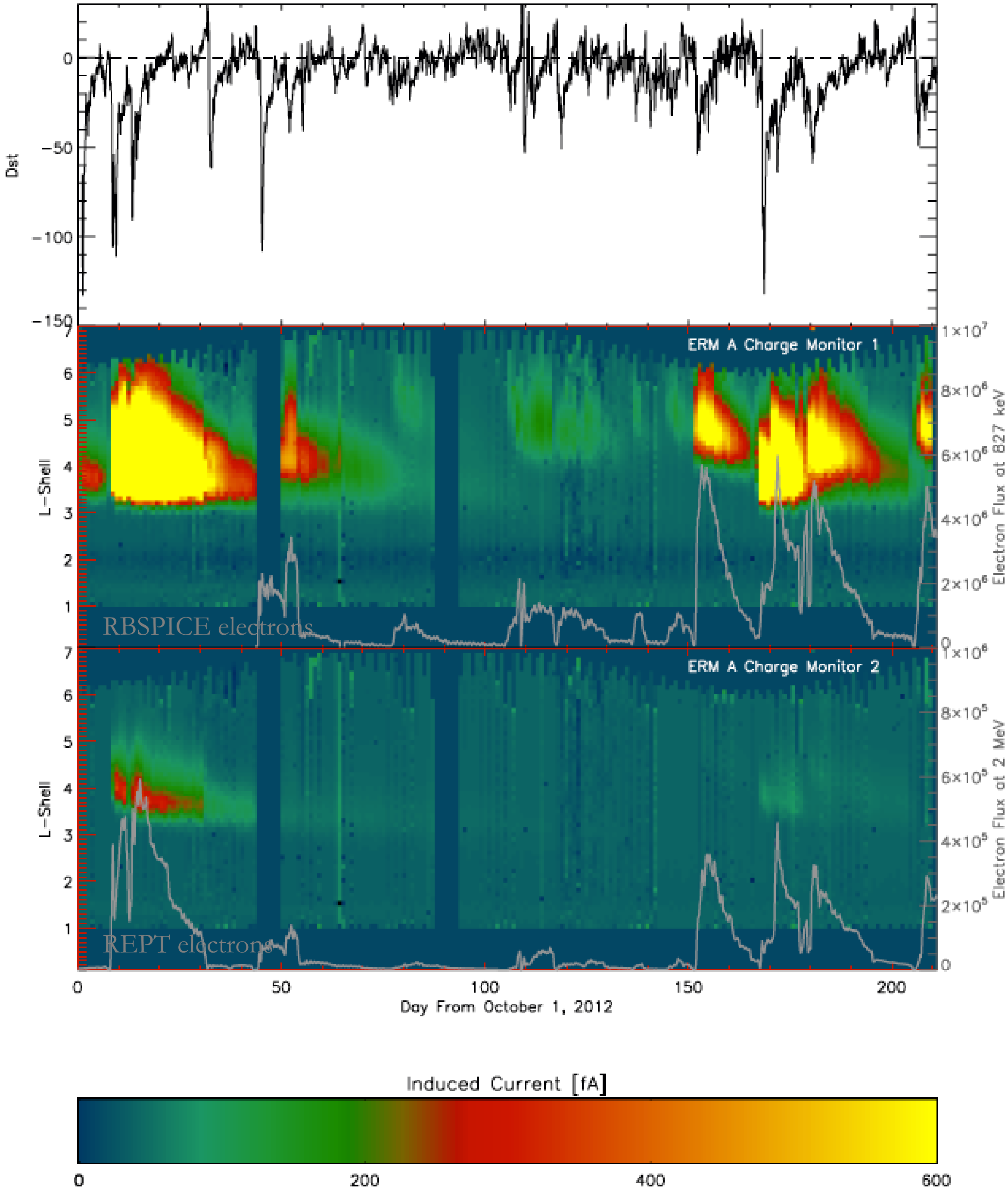

Van Allen Probes/RPS
log(Rads/sec)
-9
-8
-7
-6
-5
-4
-3
-2
OPQ L shell
7
6
5
4
3
2
1
9/1/2012
1/1/2013
5/1/2013
9/1/2013
1/1/2014
5/1/2014
9/1/2014
Date

# Internal Spacecraft Charging from the Environmental Radiation Monitors on the Van Allen Probes Spacecraft: Charging driven by solar wind conditions

*Andrew Gerrard[1], Louis Lanzerotti[1],*
*Thomas Sotirelis[2], John Goldsten[2], Barry Mauk[2]*

1. *New Jersey Institute of Technology*
2. *Applied Physics Laboratory-John Hopkins University*

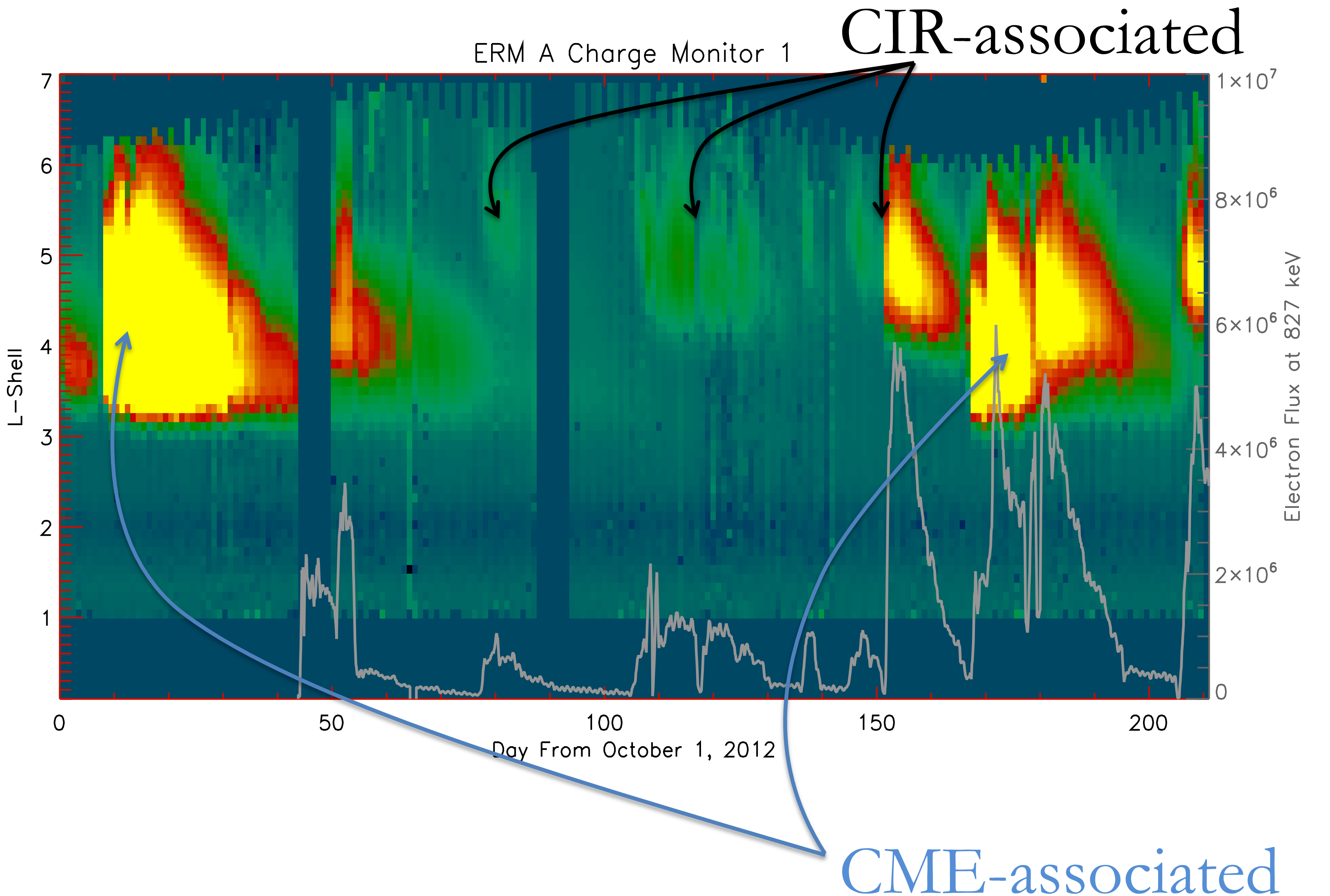
*Special Thanks to Kyungguk Min [Auburn],*
*the RBSPICE team,*
*and the larger VA Probes Team!*



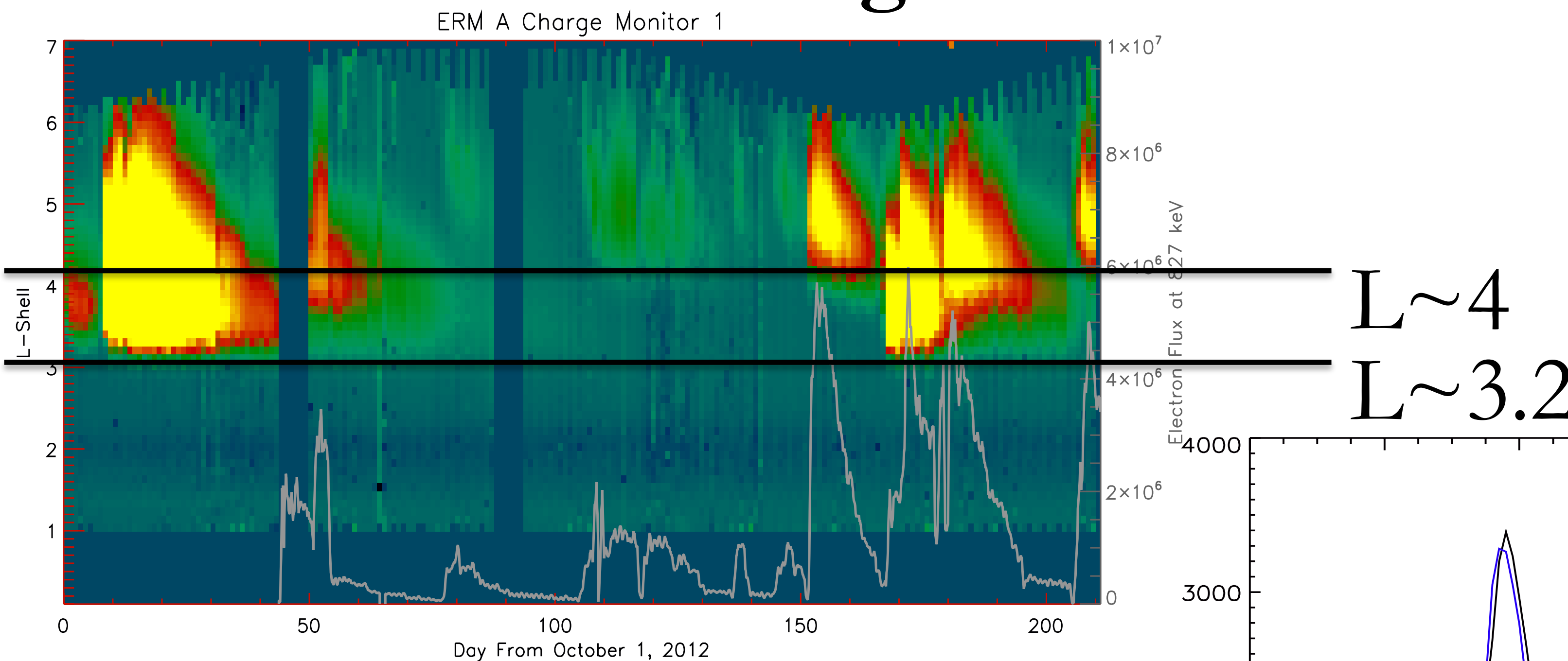

## General Characteristics

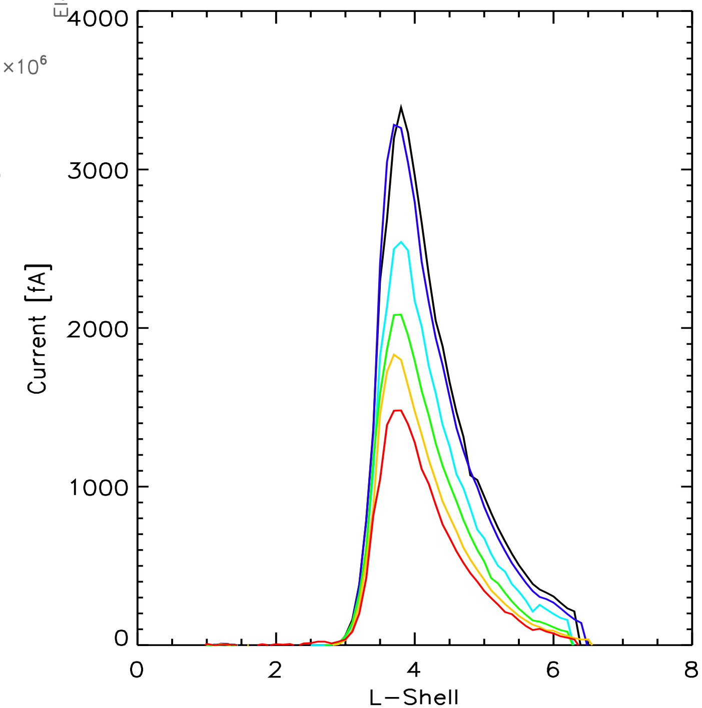
- Charge enhancements associated with ring-current activity, in turn caused by the magnetospheric response to interplanetary structures (later)
- "Background charging" of ~60-fA
- Reduction of charging in the slot region

# Charging Associated with Interplanetary Structures



# "Charge Floors"



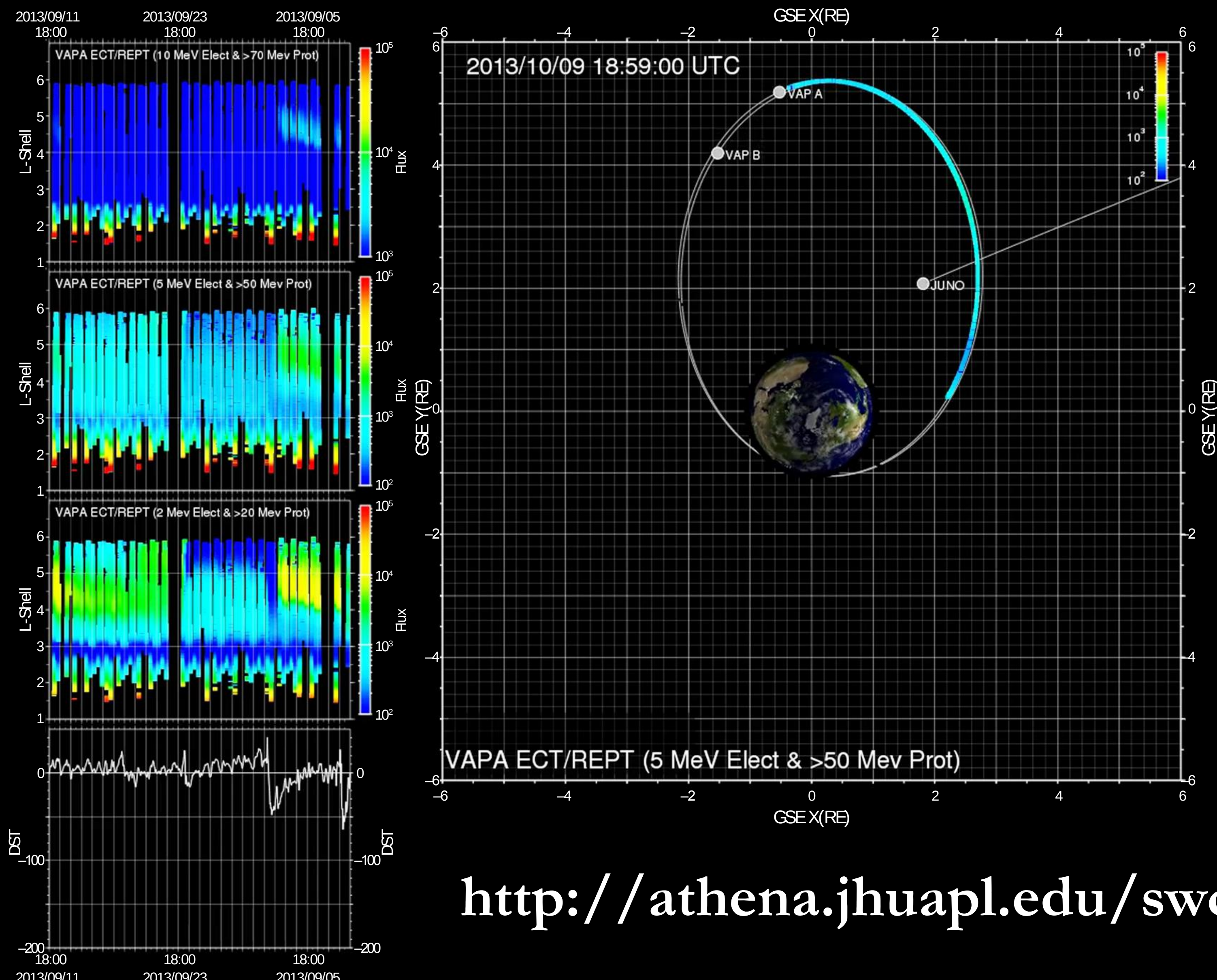

- L~3.2 floor expected due to slot region associated with these energies
- Unclear as to the L~4 floor…

# ERM Conclusions To Date

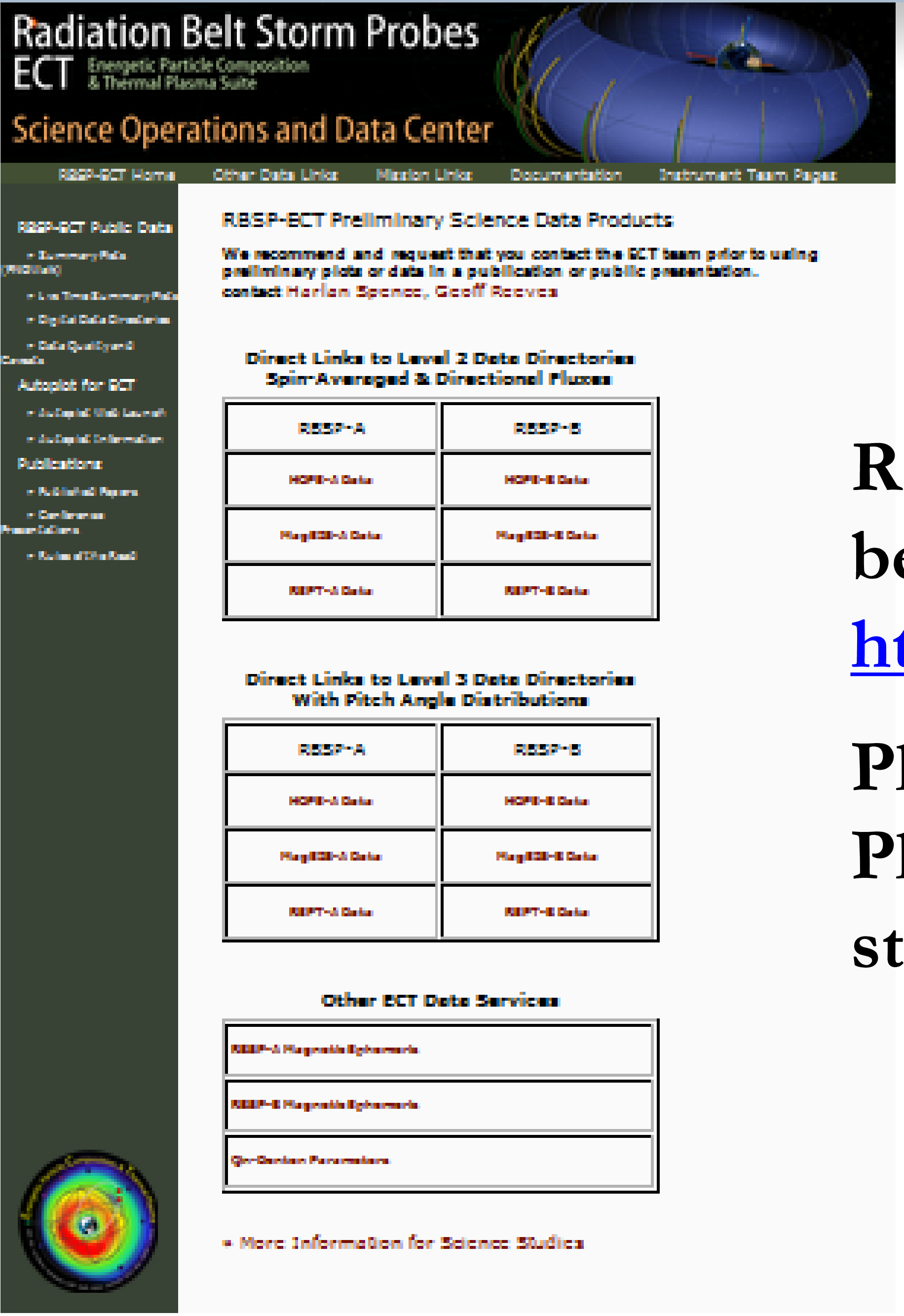
- The next generation of spacecraft charging models (e.g., AE9 "V.20") will require synoptic charging data.
- The VA Probes ERM can provide such data.
- Already have ongoing catalog of CMEs, CIRs, and ULF associated charging
- As VA Probes precess through one complete orbit of Earth [and more], we will be able to address location dependence

# Real-Time Spaceweather Data Feed from Van Allen Probes for Situational Awareness

Larry Zanetti et al.
(JHU/APL)


**http://athena.jhuapl.edu/swcontext/**

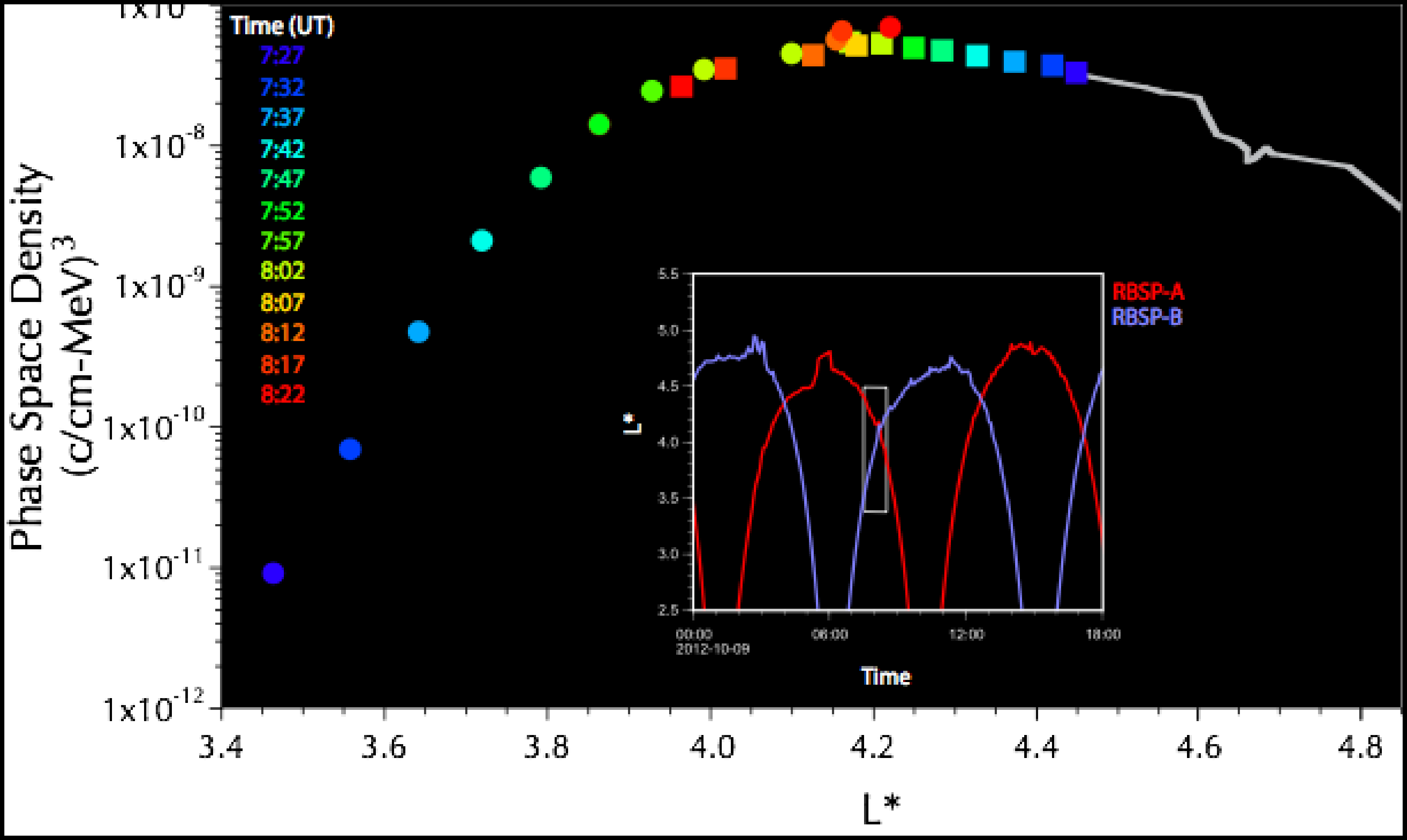



RBSP-ECT L2 and L3 data can be found at: http://www.rbsp-ect.lanl.gov/

Please visit "caveat" section; Please contact us for help as you start using ECT data

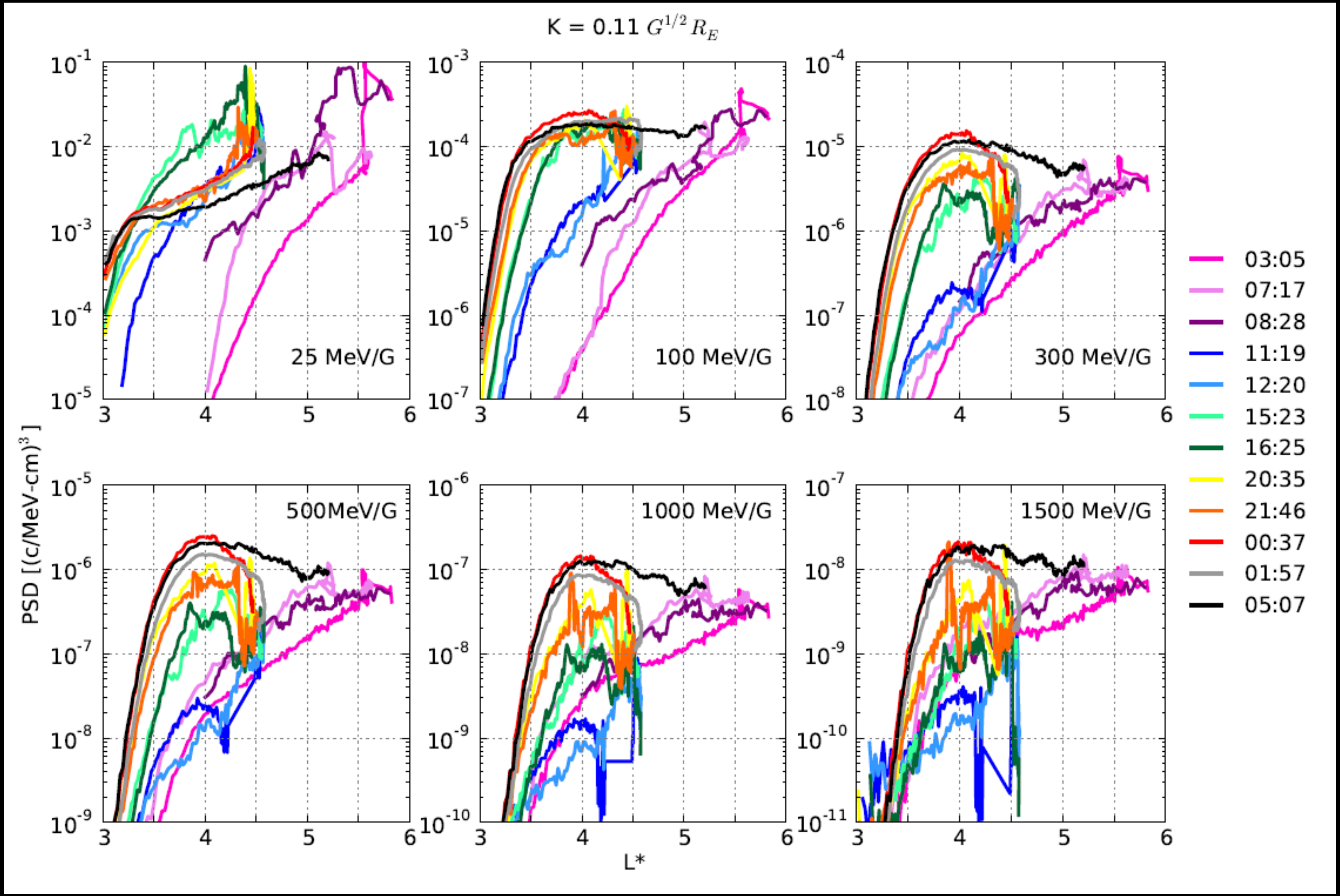
# Another Mystery Resolved

## They reach the peak at the same time and measure the same PSD to within a factor of 1.2



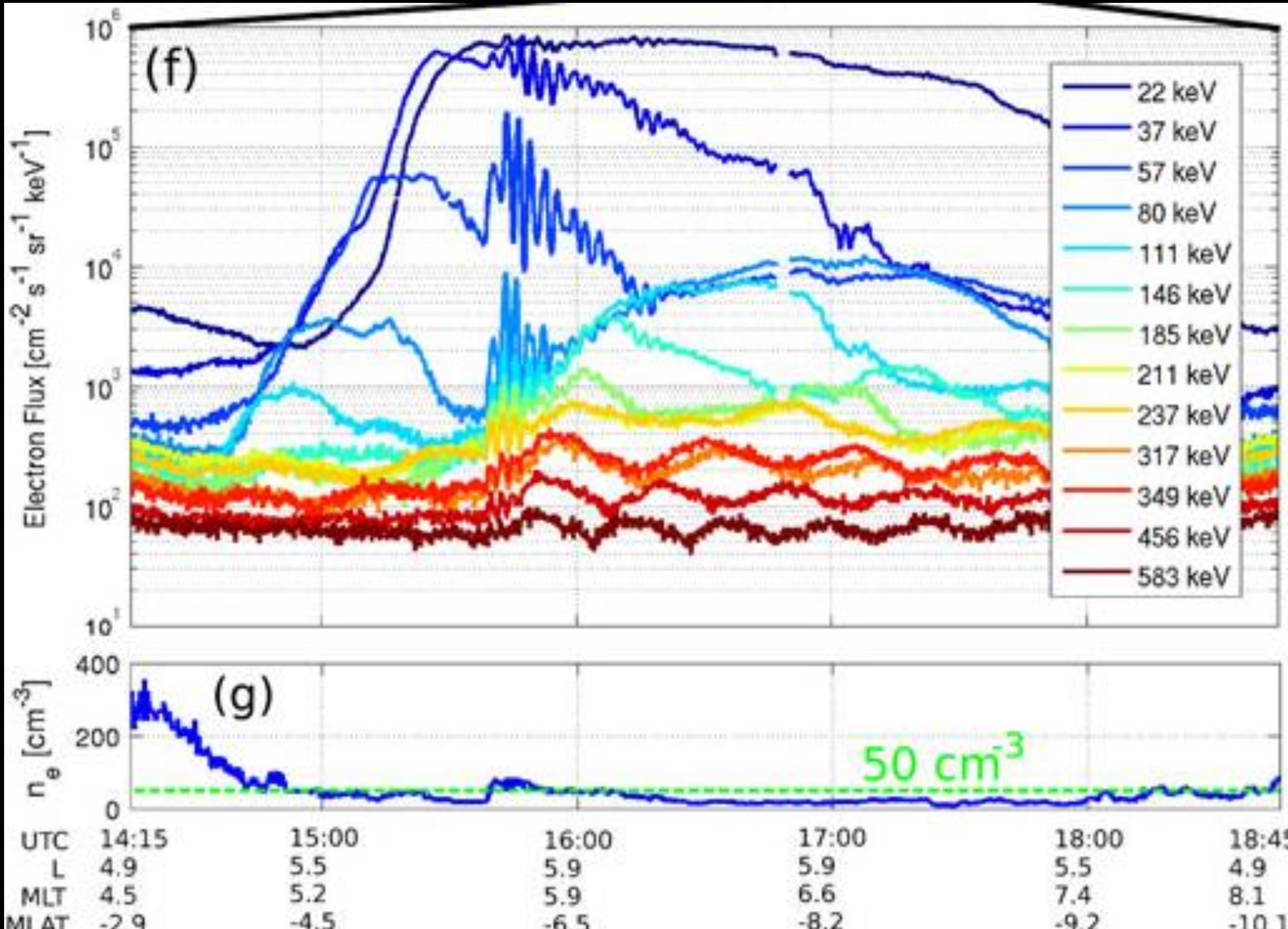

A is Inbound - B is Outbound

# And Local Acceleration Happens Over and Over and Over…




**Ability to cast data into phase space density in adiabatic coordinates allows us to identify and quantify seed population, spatial locations, acceleration time scales, etc., more mysteries revealed (Boyd et al., GRL, 2013)**

**Boyd, A. J., H. E. Spence, S. G. Claudepierre, J. F. Fennell, J. B. Blake, D. N. Baker, G. D. Reeves, D. L. Turner, and H. O Funsten, The role of radiation belt seed population in the March 17, 2013 acceleration event, Geophys. Res. Lett., under review, 2013.**

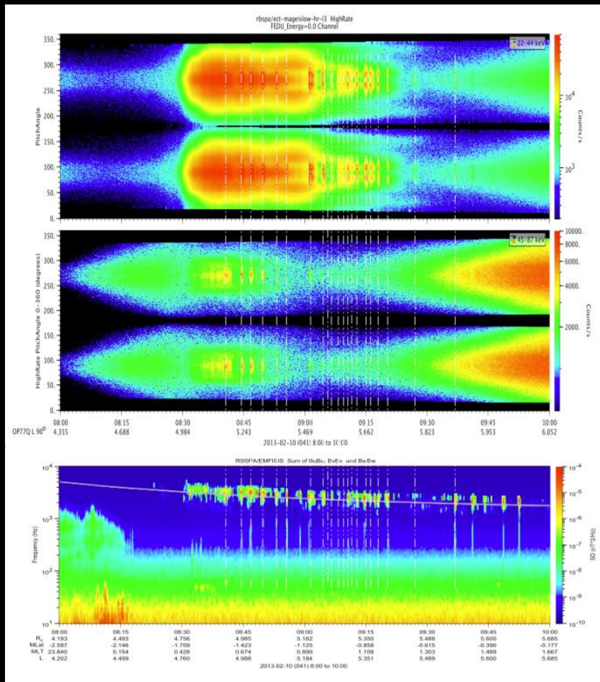


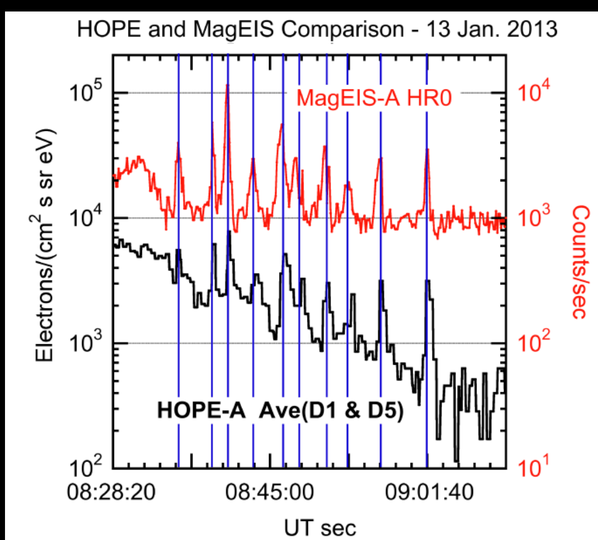

In addition to local acceleration owing to gyro-resonance, there are also ULF wave modes that resonate globally with gradient drifting electrons

Another acceleration mechanism that dominates at times (Claudepierre et al., GRL, 2013; Mann et al., Nature Comm., 2013)

From S. G. Claudepierre, et al., , Van Allen Probes observation of drift-resonance between poloidal mode ultra-low frequency waves and 60 keV electrons, Geophys. Res. Lett., doi: 10.1002/grl.50901, 2013.

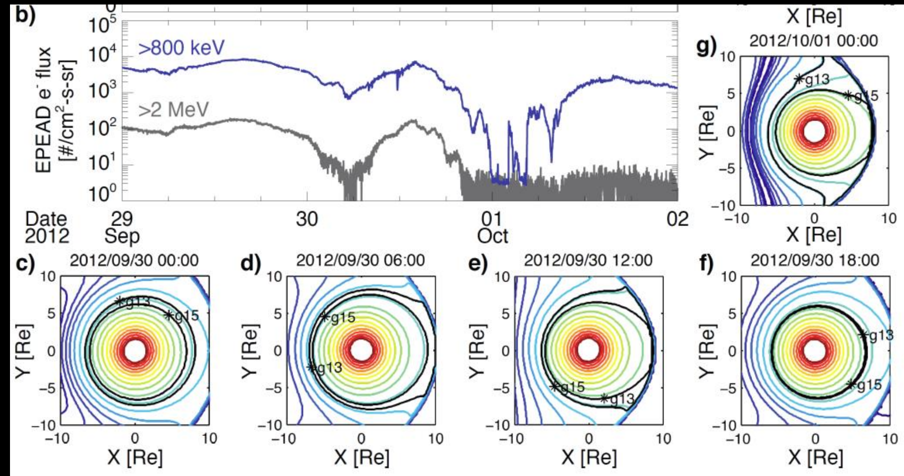
See also Dai, L., et al., , Excitation of Poloidal standing Alfven waves through the drift resonant wave-particle interaction, Geophys. Res. Lett., DOI: 10.1002/grl.50800, 2013.





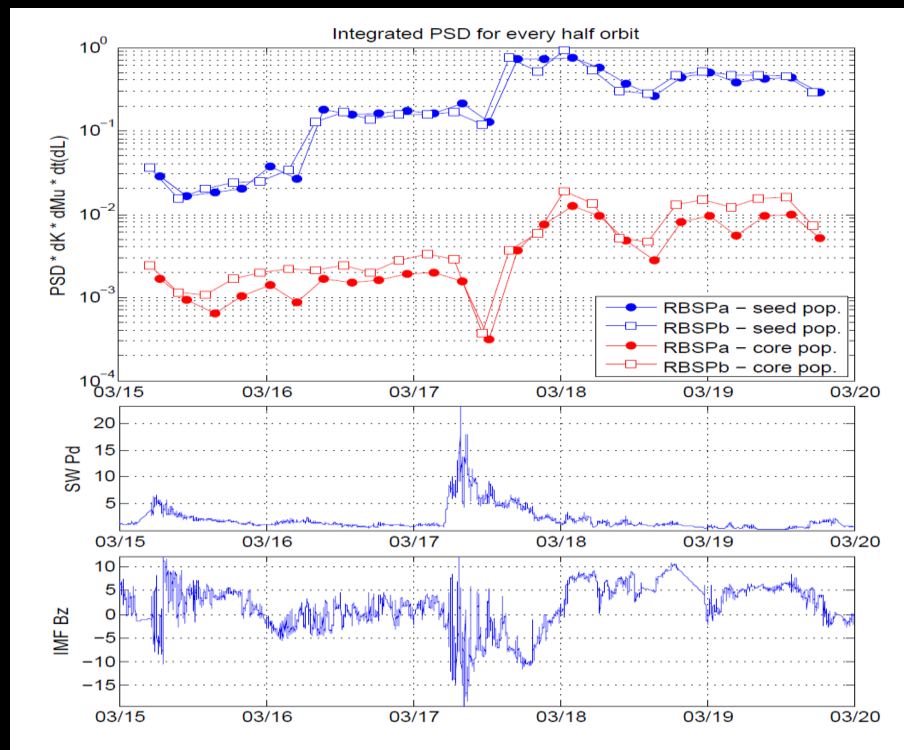


From Fennell et al., GRL, 2013.





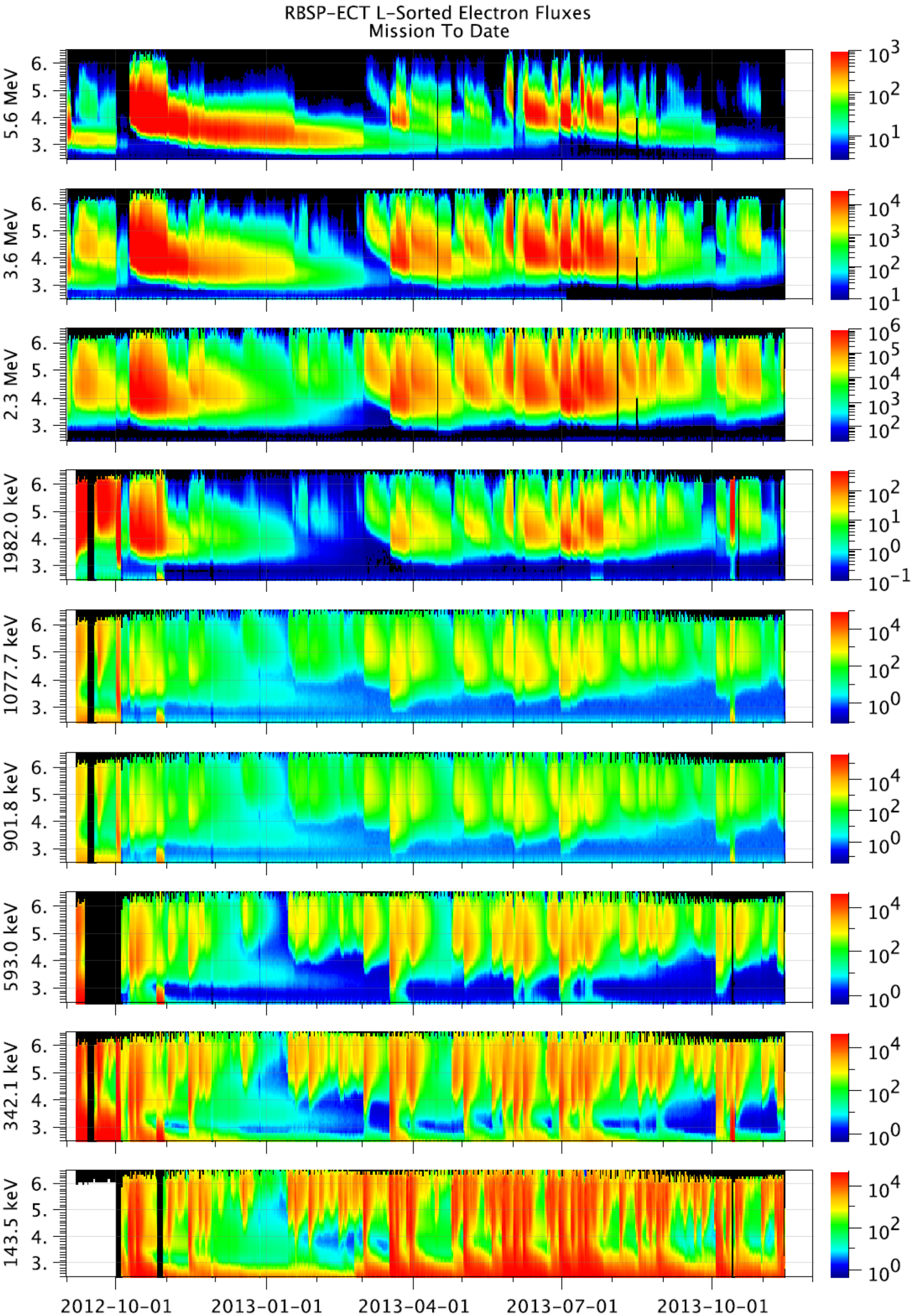
From Turner et al., JGR, 2013.





From Spence et al., Tuesday at Fall AGU….

- We see with exquisite detail how rad belt particles are modified by bursts of waves, some toward the loss cone (Fennell et al., GRL, 2013) which has global consequences (Crew et al., JGR, 2013)
- Some loss also occurs through magnetopause (Turner et al., JGR, 2013)
- We can finally quantify total radiation belt content in order to assess importance of losses (Spence et al., AGU Tue talk)

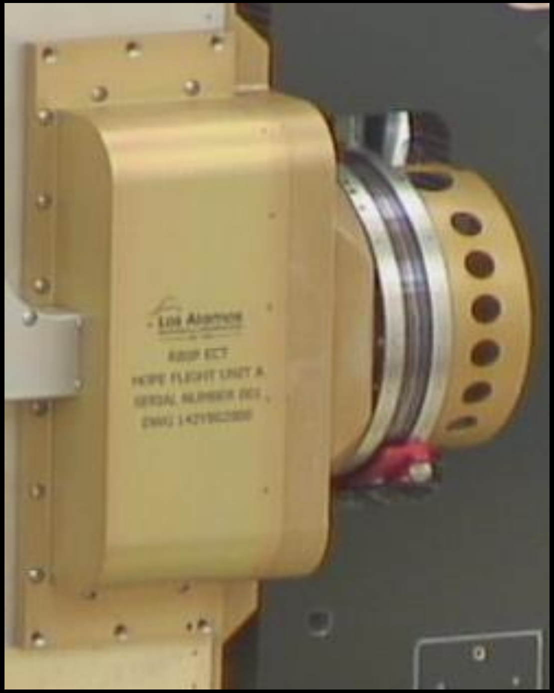



## Summary

- The radiation belt is an area still ripe for discovery, despite its 50+ year history of study
- Radiation belt dynamics are scientifically compelling, universally relevant, and important to variety of user communities
- Transformational measurements made by RBSP-ECT along with other instruments are achieving mission science objectives
- You can learn more about the mission at: vanallenprobes.jhuapl.edu
- ECT L3 data can be found at: http://www.rbsp-ect.lanl.gov/

# Meet the RBSP-ECT Instrument Suite from low to high: HOPE, MagEIS, and REPT

HOPE = Helium, Oxygen, Protons, Electrons



*Funsten et al., SSR, 2013*

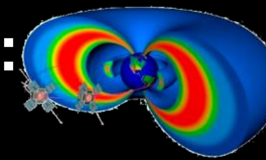
*Blake et al., SSR, 2013*

MagEIS = Magnetic Electron Ion Spectrometer

REPT = Relativistic Electron Proton Telescope

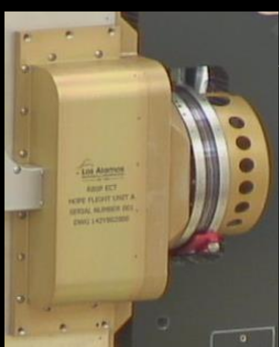
*Baker et al., SSR, 2012*

# RBSP-ECT Instrument Health and Performance: Meets or Exceeds Requirements



Energetic Particle, Composition, & Thermal Plasma

UNH - BU - Los Alamos - Aerospace - LASP - SwRI - NOAA - Dartmouth - UCLA - BAS - ONERA - U. Alberta



HOPE

MagEIS

REPT

- **All 12 ECT instrument packages operating beautifully: 1 HOPE, 4 MagEIS (1 “Low”, 2 “Mediums”, 1 “High” [w/ ion telescope], and 1 REPT per s/c)**
- **All RBSP-ECT instruments in science mode and returning high quality data (all GREEN)**
- **ECT inflight performance meets or exceeds measurement requirements**
- **Continue to tweak settings, thresholds, etc.**
- **Level 3 data available at ECT SOC (managed by LANL)**

# Calculate TRBEC II

- 3 Invariant action integrals in dipole field (Schulz, Geomagnetism, 1991)
  - $m_0$: electron mass, e: electron charge, c: speed of light, $\mu_0$: dipole moment

$$J_1 = \frac{2\pi m_0 c}{e}\mu,$$

$$J_2 = \sqrt{8 m_0 \mu} K,$$

$$J_3 = -\frac{2\pi e \mu_0}{c R_E L^*},$$

- Jacobian determinant:

$$\frac{\partial(J_1, J_2, J_3)}{\partial(\mu, K, L^*)} = \begin{vmatrix} \frac{\partial J_1}{\partial \mu} & \frac{\partial J_1}{\partial K} & \frac{\partial J_1}{\partial L^*} \\ \frac{\partial J_2}{\partial \mu} & \frac{\partial J_2}{\partial K} & \frac{\partial J_2}{\partial L^*} \\ \frac{\partial J_3}{\partial \mu} & \frac{\partial J_3}{\partial K} & \frac{\partial J_3}{\partial L^*} \end{vmatrix} = \frac{8\sqrt{2}\pi^2 m_0^{3/2} \mu_0}{R_E} \frac{\sqrt{\mu}}{L^{*2}}.$$

# Calculate TRBEC III

- Unit conversion from phase space density data using natural units

$$1\left(\frac{c}{\mathrm{cm\ MeV}}\right)^3 = 2.585 \times 10^{26}\left(\frac{c}{R_E\ \mathrm{MeV}}\right)^3.$$

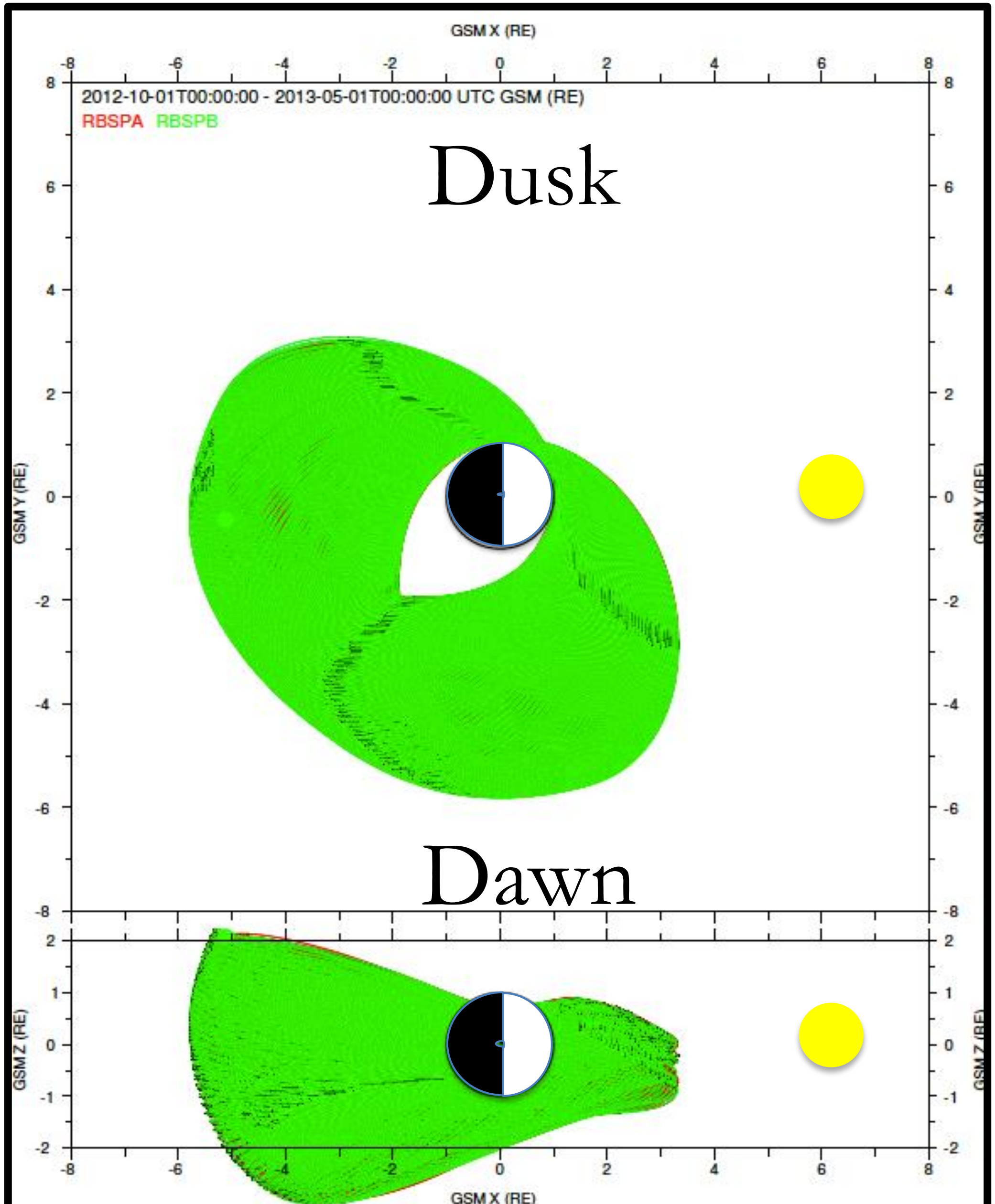
- Mass: $m_0 = 0.511$ MeV/$c^2$
- Magnetic field: $\mu_0 = 0.311$ G $R_E^3$
- $c = 1$, $R_E = 1$
- μ [MeV/G], K [G $R_E^3$] , L*

## Environmental Radiation Monitors on VA Probes

The ERM packages are described in detail in Goldsten et al. [2012].

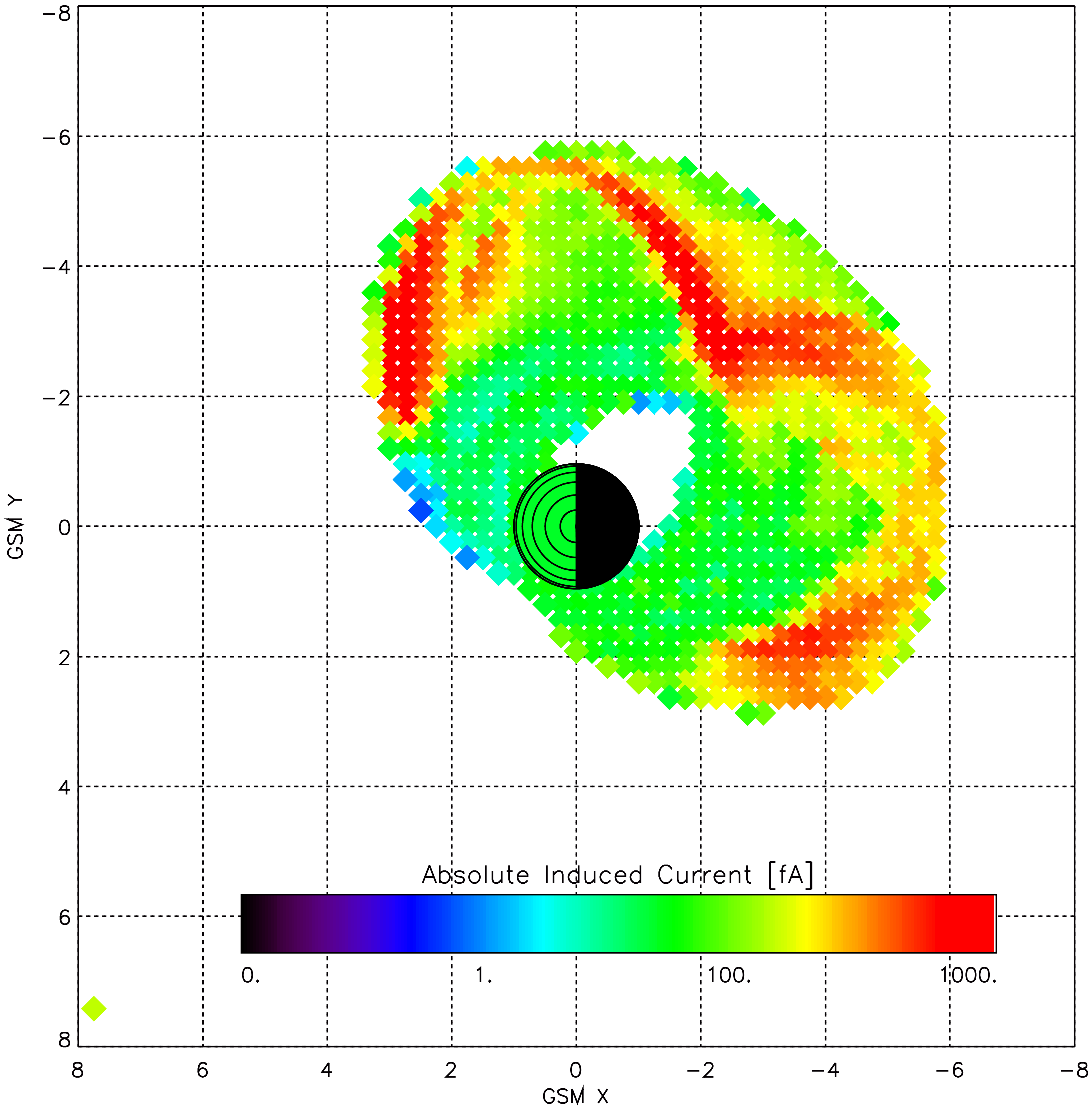
Power and data for the ERM instruments are on the same interface as the Radiation Belt-Storm Probes Ion Composition Experiment (RBSPICE) instrument Mitchell et al. [2013].

We focus on the two spacecraft charge monitors that are part of each ERM package, CM1 and CM2, each under different




## Orbits and Data

- The data shown herein were obtained during the first 7-months (October 1, 2012-April 30, 2013) of the Van Allen Probes mission.

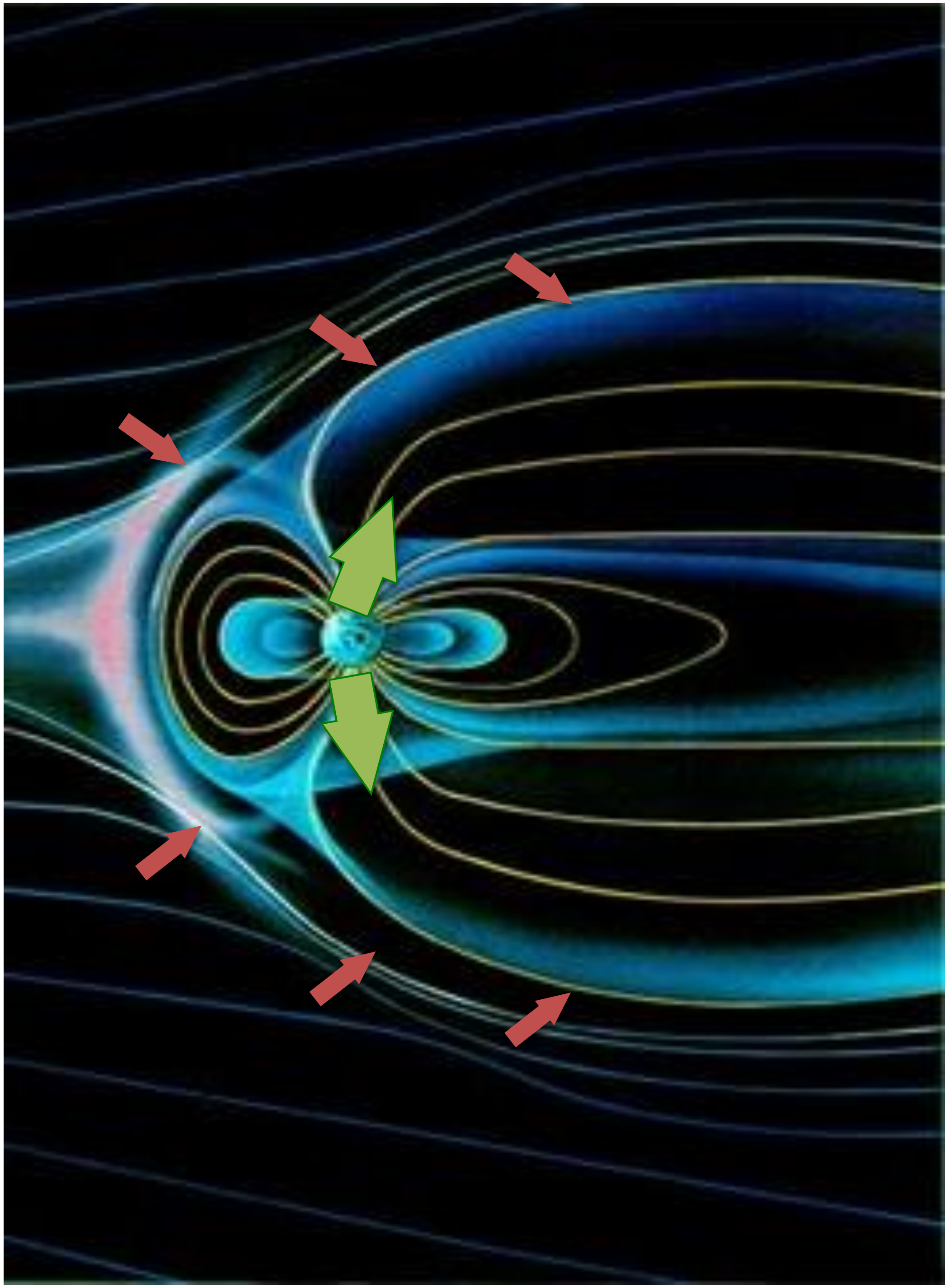



## General Characteristics

- Charge enhancements associated with ring-current activity, in turn caused by the magnetospheric response to interplanetary

## Cautionary Note

- Phase 1: Interplanetary structure enters Earth's space environment
- Phase 2:



**Cautionary Note**

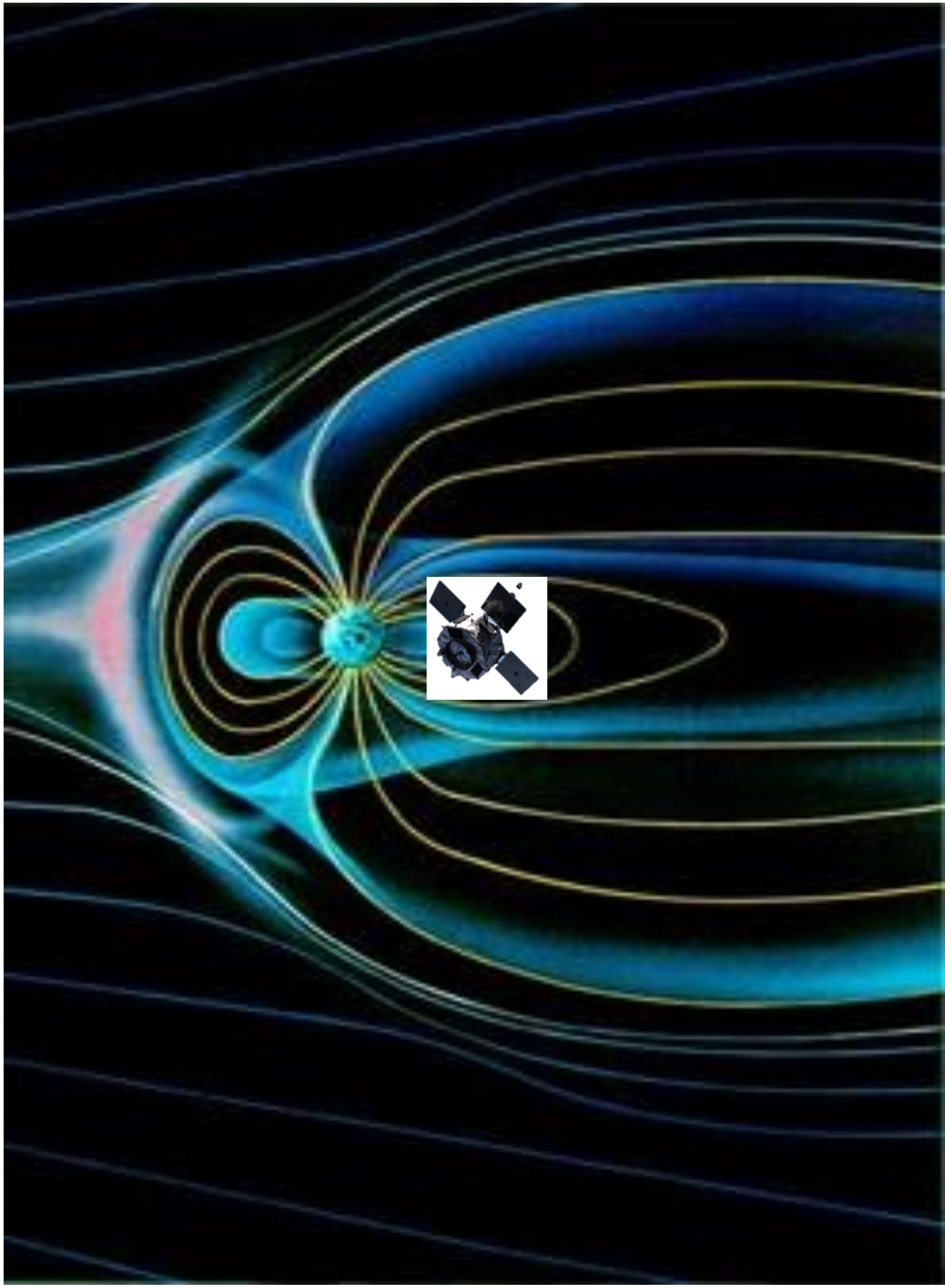
- Phase 1: Interplanetary structure enters Earth's space environment

- Phase 2: ???

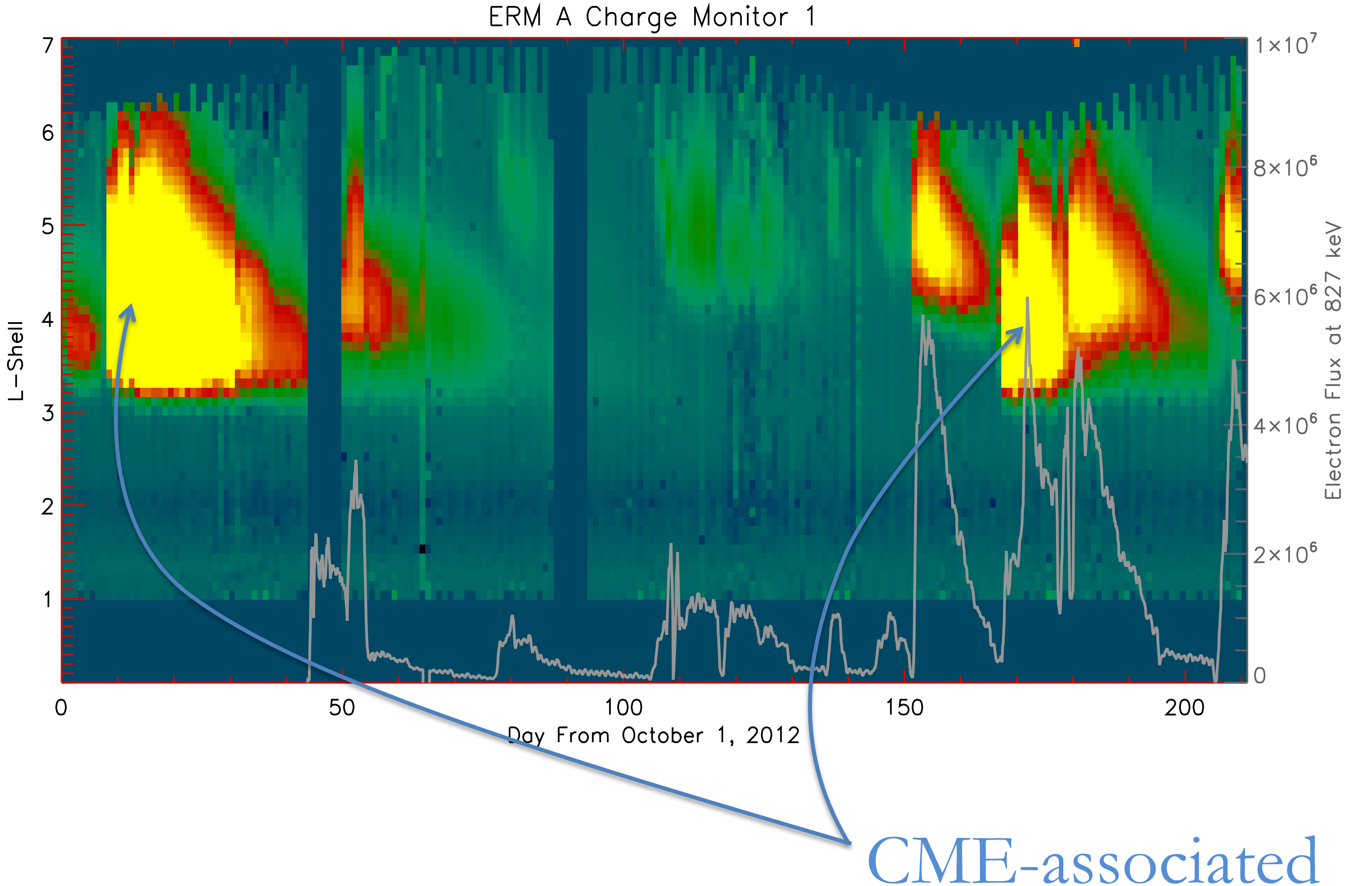
- Phase 3

**Cautionary Note**

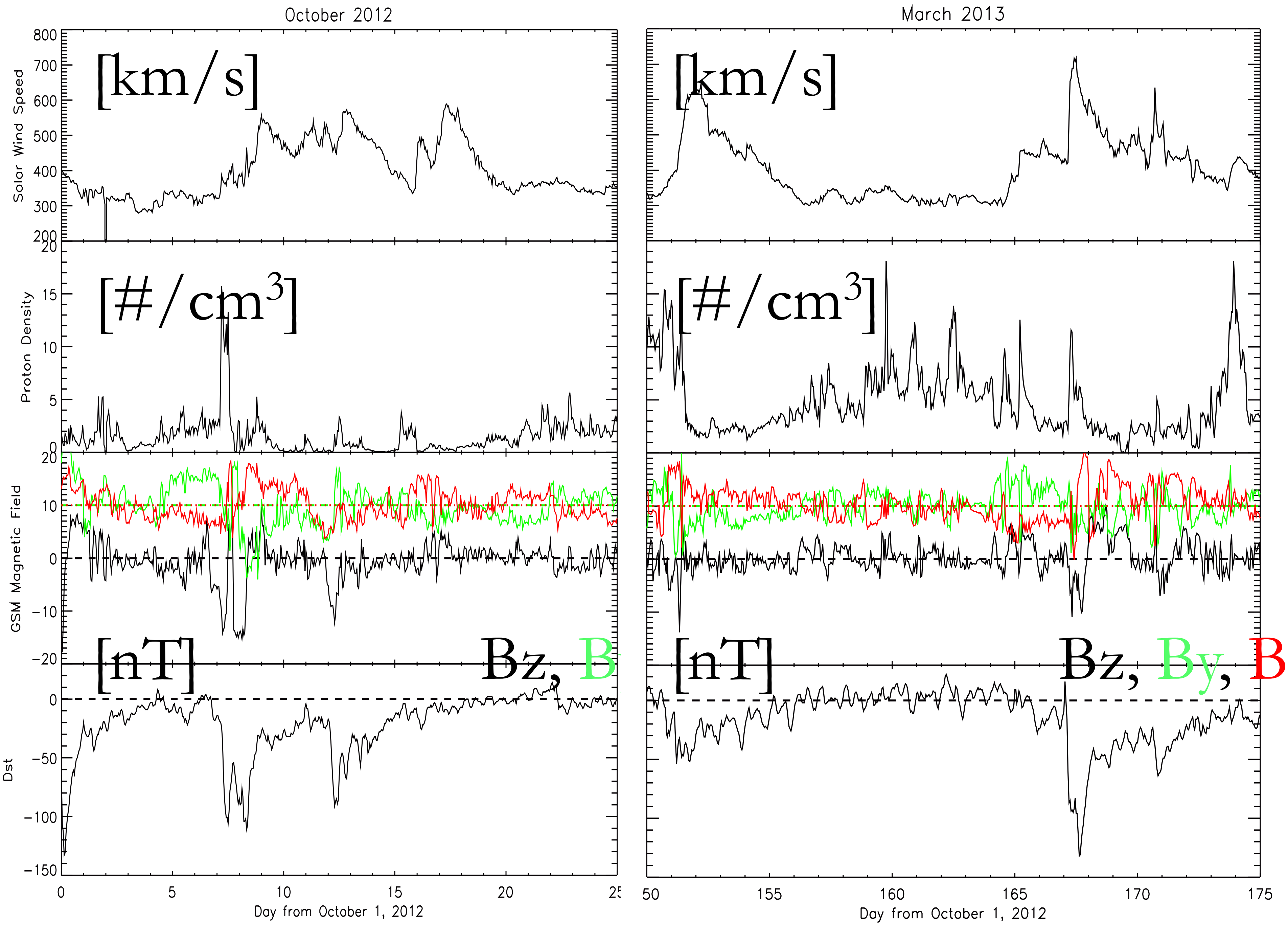
- Phase 1: Interplanetary structure enters Earth’s space environment
- Phase 2: ???

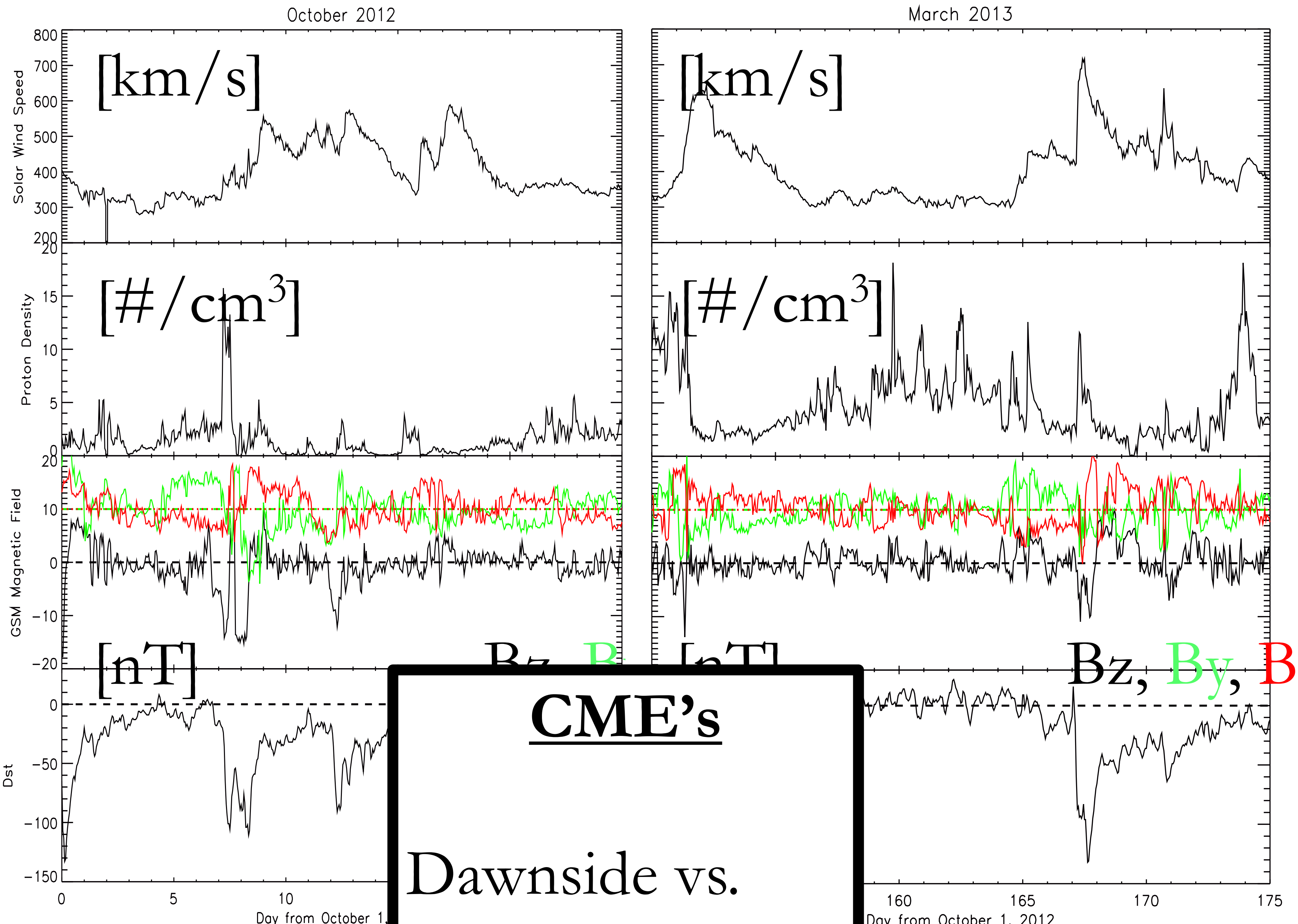


# Two CMEs



ERM A Charge Monitor 1
L−Shell
Electron Flux at 827 keV
Day From October 1, 2012
0
50
100
150
200
1
2
3
4
5
6
7
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
CME-associated

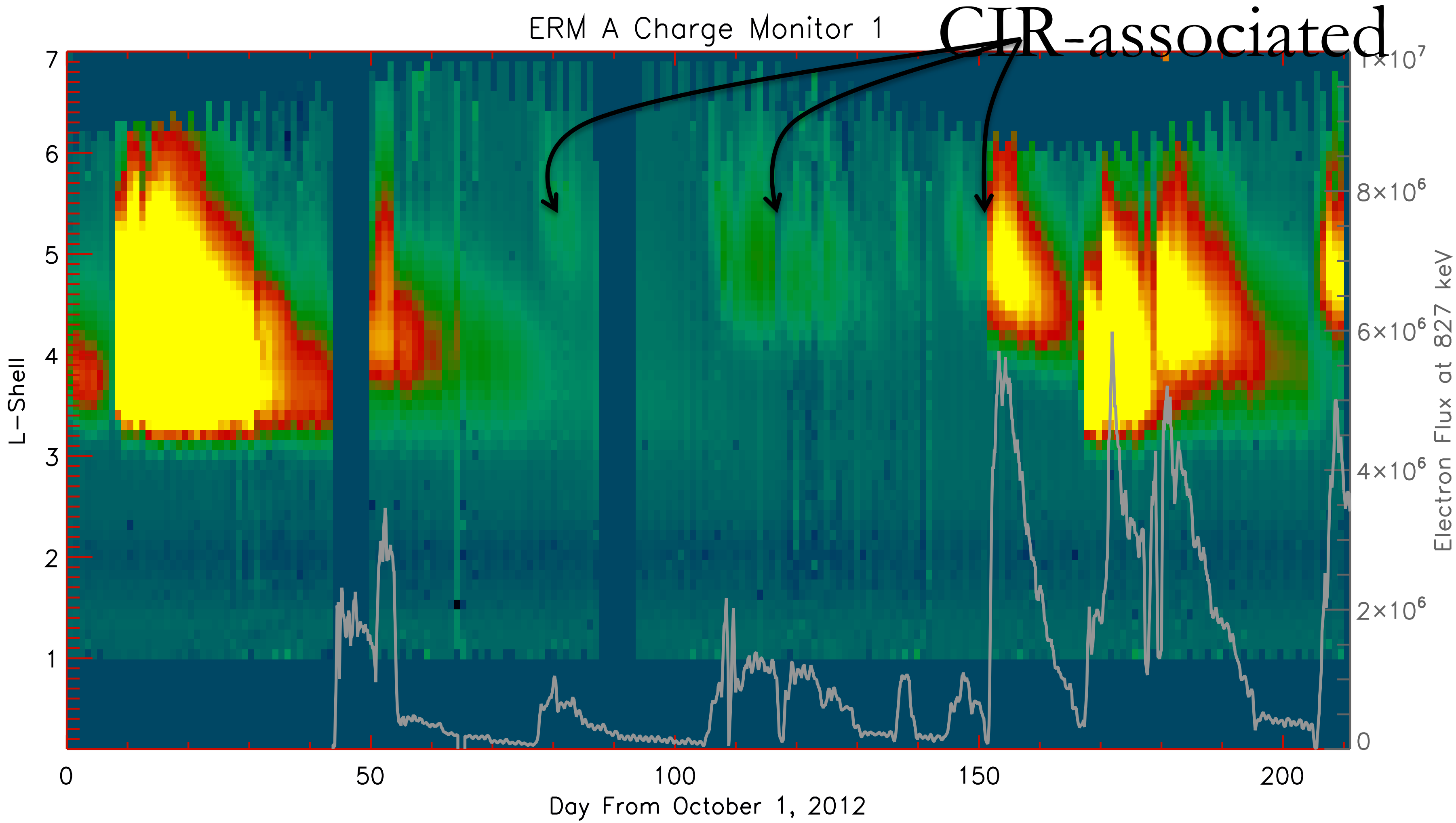

October 2012
March 2013
Solar Wind Speed
[km/s]
Proton Density
[#/cm3]
GSM Magnetic Field
[nT]
Bz, By, Bx
Dst
Day from October 1, 2012



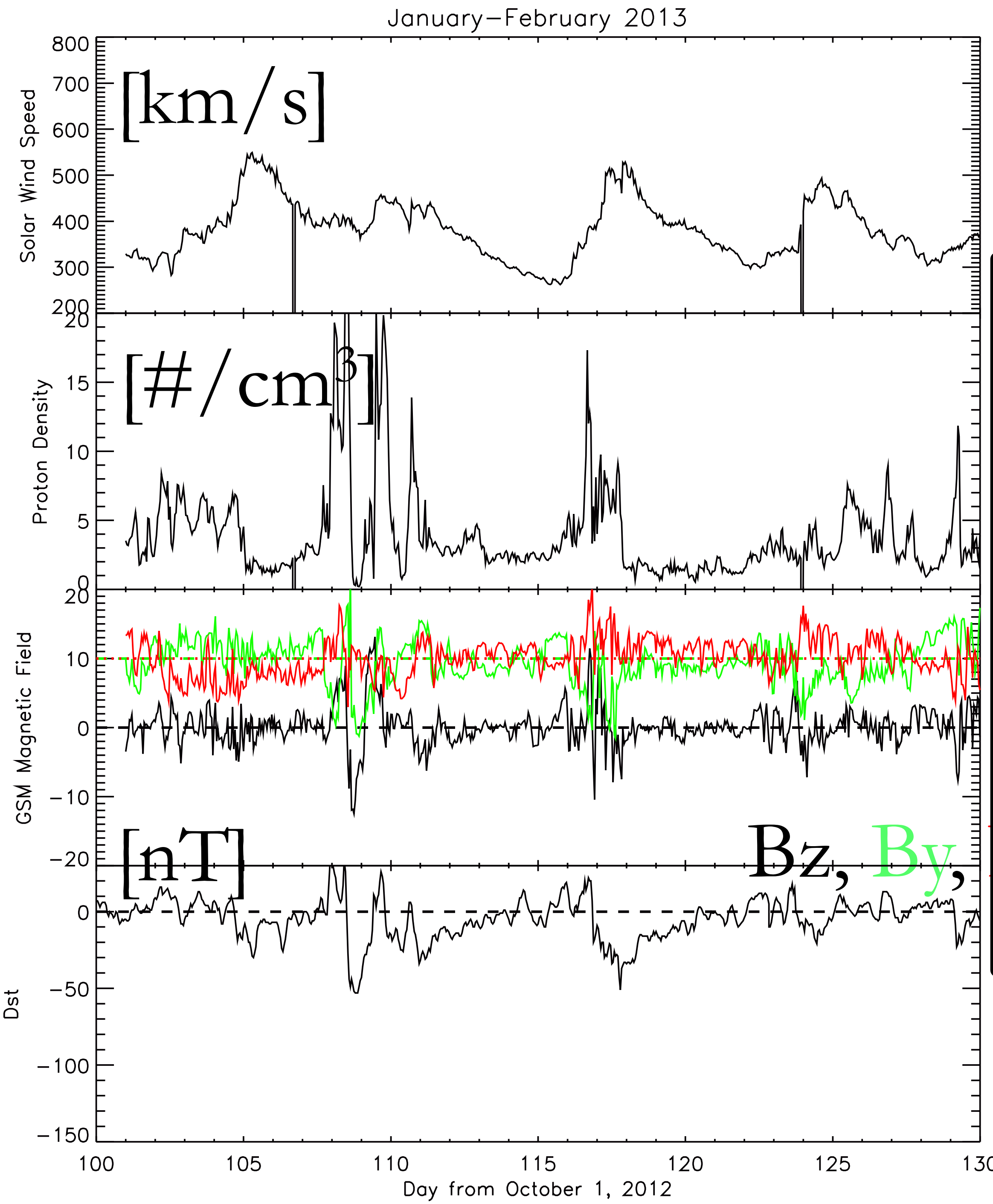

**CME's**

Dawnside vs. nightside

# CIRs



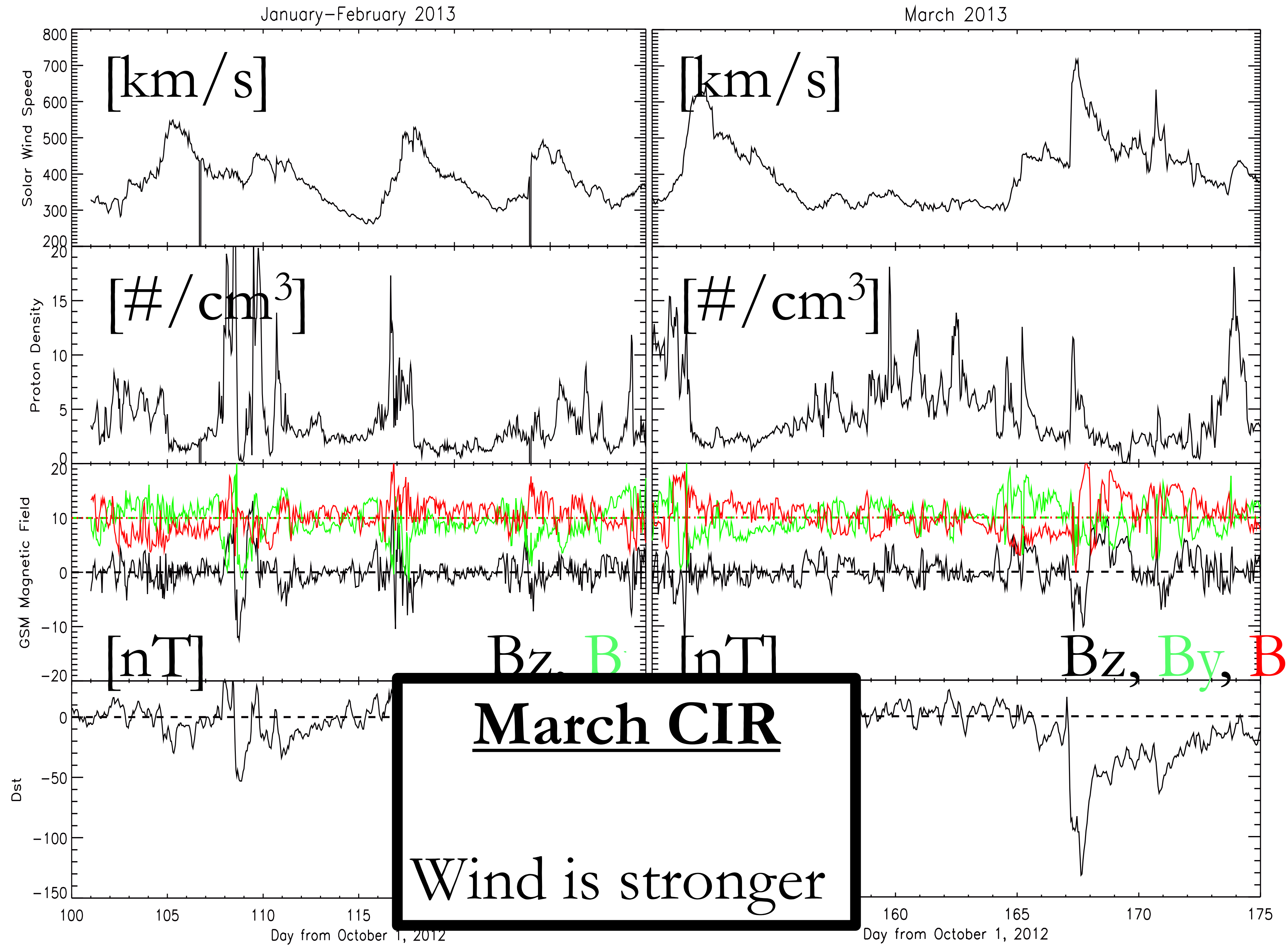

CME-associated



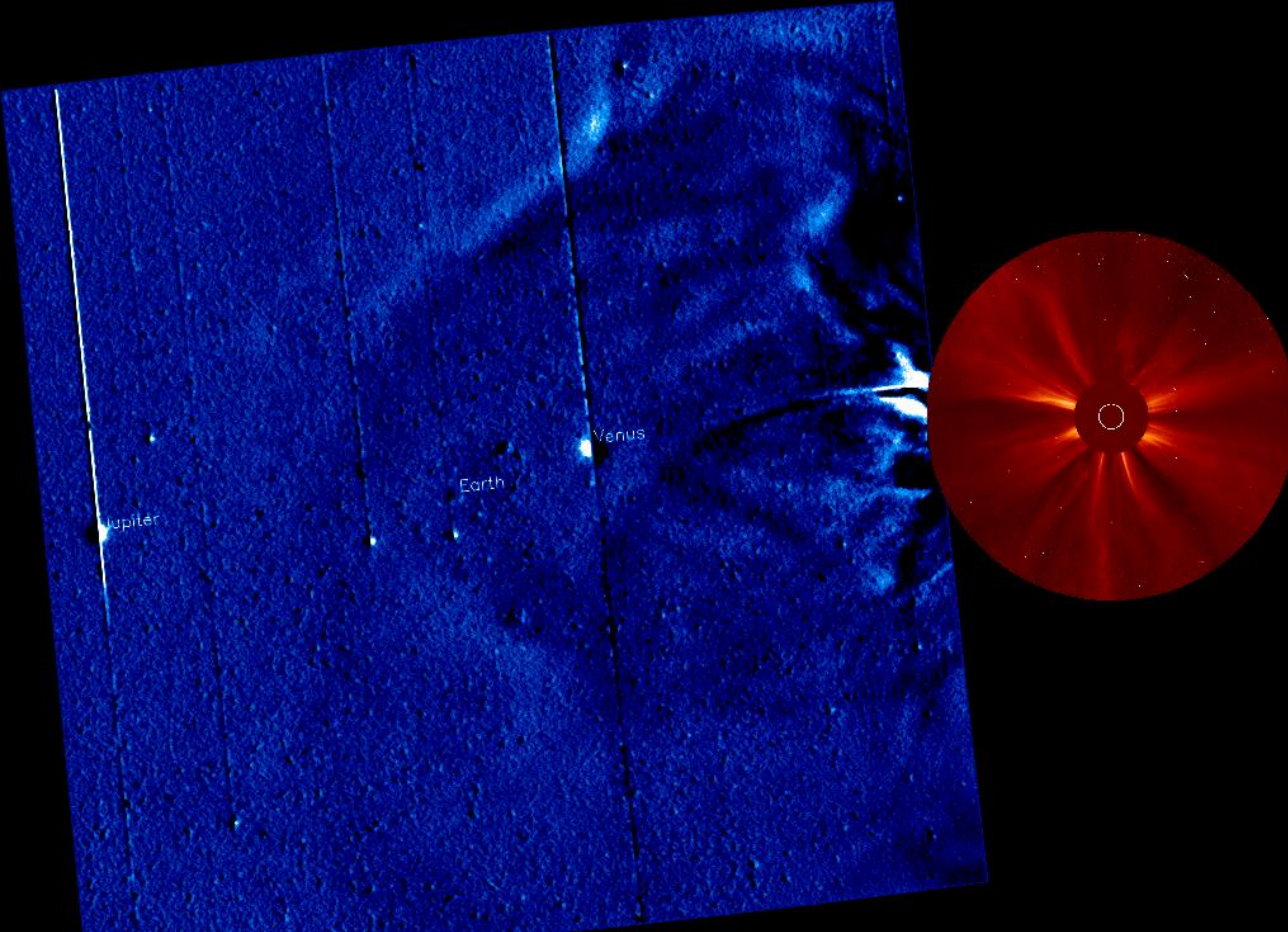

## CIRs

Dawnside to nightside

Bz is nominally 0, or negative during low ion densities



January-February 2013
March 2013
Solar Wind Speed
[km/s]
Proton Density
[#/cm³]
GSM Magnetic Field
[nT]
Bz, By, Bx
Dst
Day from October 1, 2012
March CIR
Wind is stronger




COR2A + HI1A 20140108 07:05 UT